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(54) **ILLUMINATION SYSTEM OF A MICROLITHOGRAPHIC PROJECTION EXPOSURE APPARATUS**

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USPC 355/53, 55, 67–71
See application file for complete search history.

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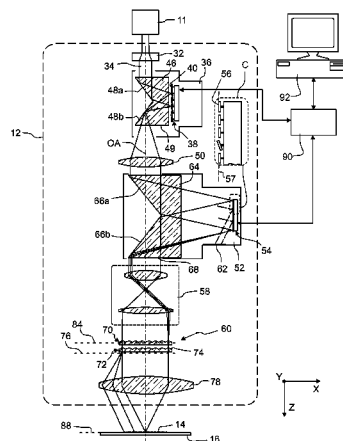(74) *Attorney, Agent, or Firm* — Fish & Richardson P.C.

(57) **ABSTRACT**

An illumination system includes an optical integrator having a plurality of light entrance facets, whose images at least substantially superimpose in a mask plane. A spatial light modulator transmits or reflects impinging projection light in a spatially resolved manner. A pupil forming unit directs projection light onto the spatial light modulator. An objective images a light exit surface of the spatial light modulator onto the light entrance facets of the optical integrator so that an image of an object area on the light exit surface completely coincides with one of the light entrance facets. A control unit controls the spatial light modulator such that along a scan direction a length of an image, which is formed on a mask from a light pattern in the object area, gradually increases at a beginning of a scan cycle and gradually decreases at the end of the scan cycle.

21 Claims, 16 Drawing Sheets

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                    7/70425 (2013.01)

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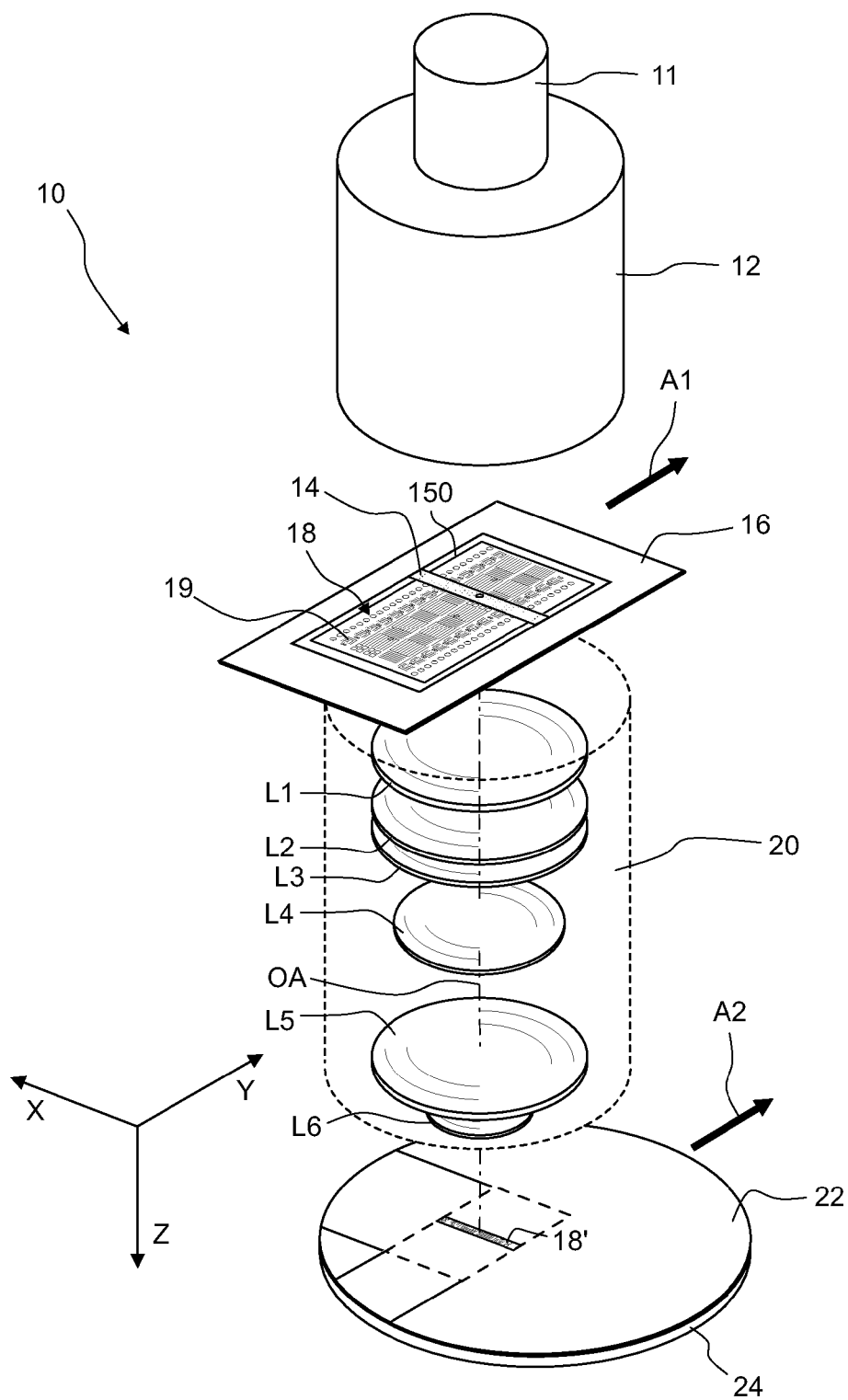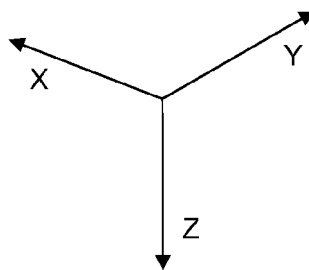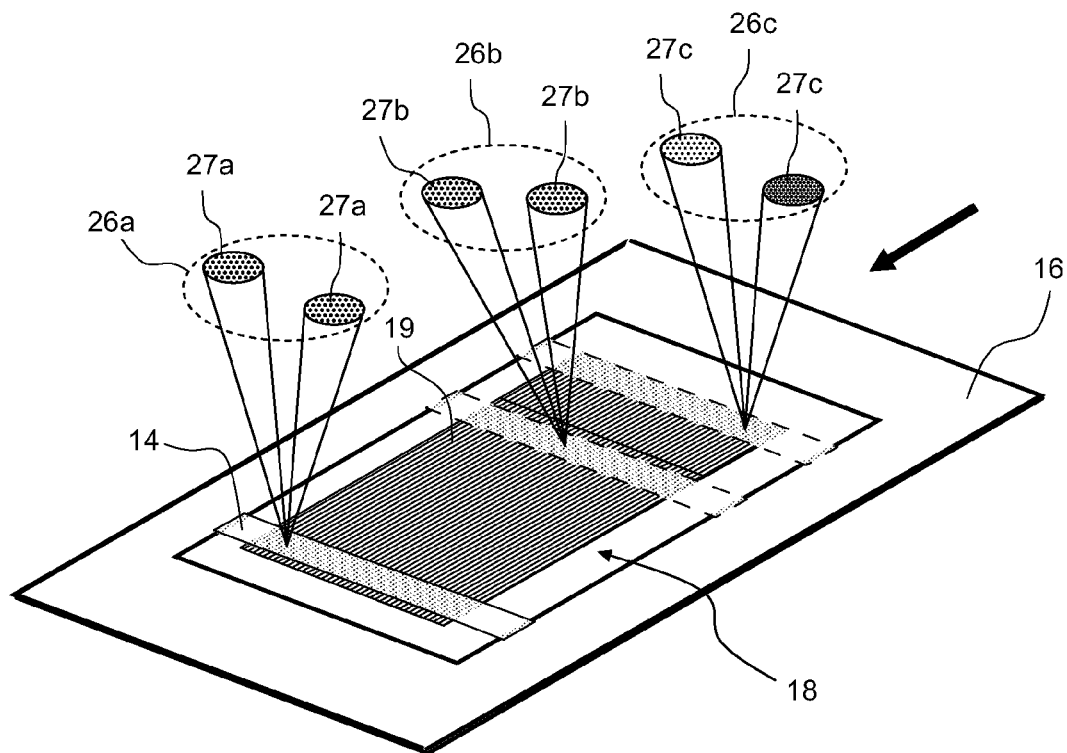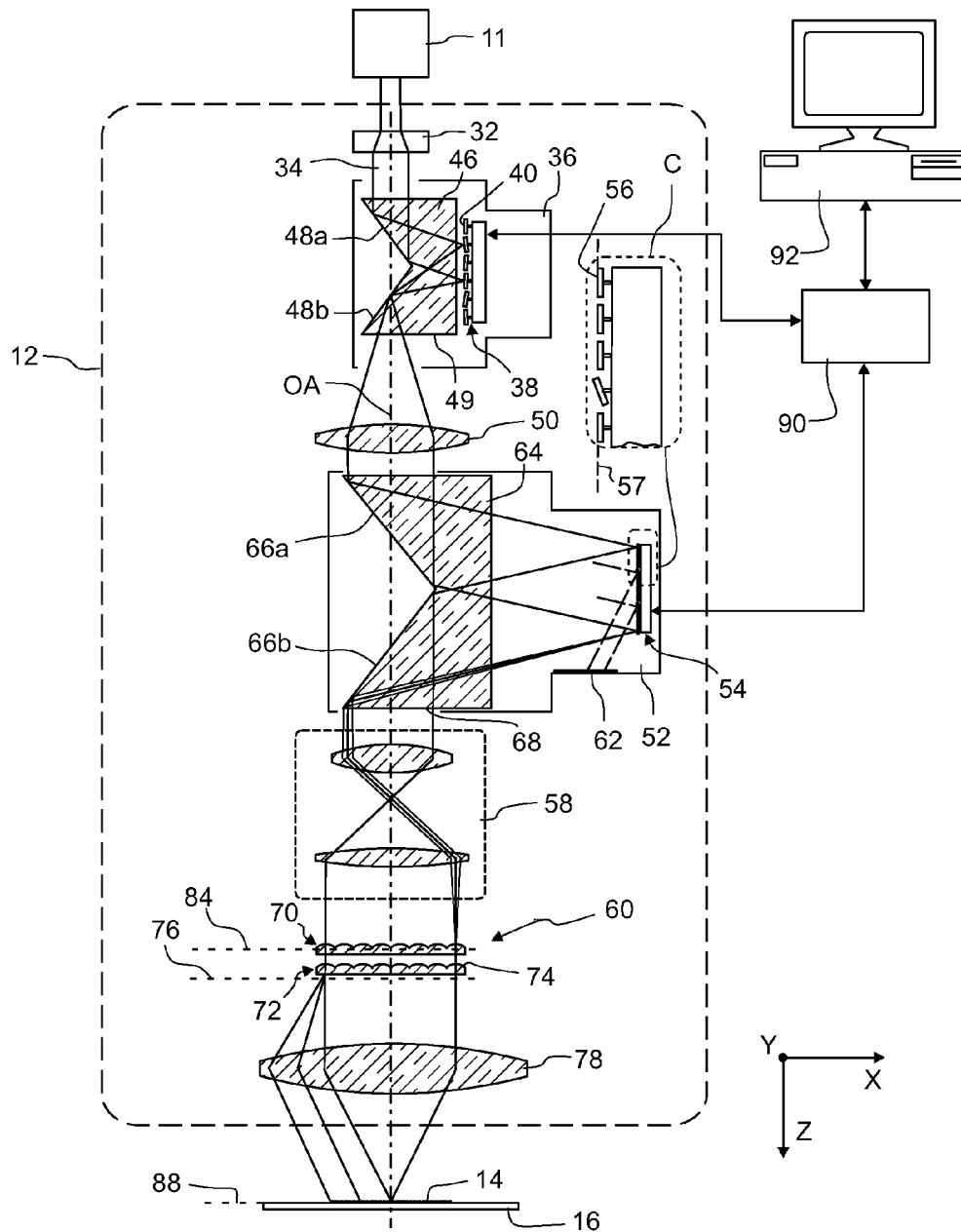
Fig.1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9
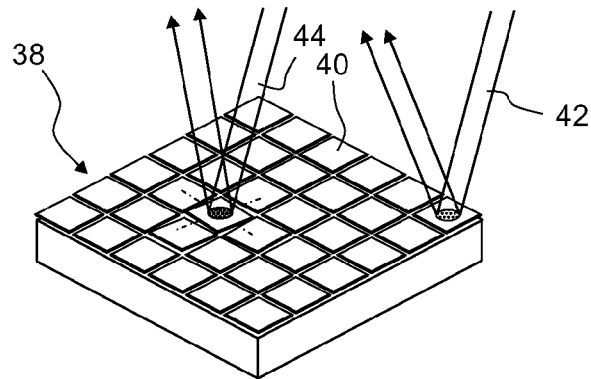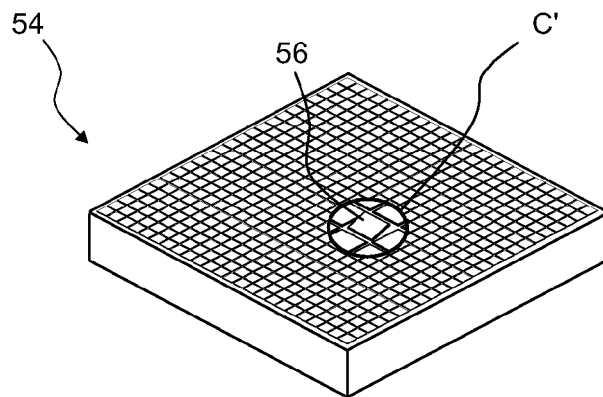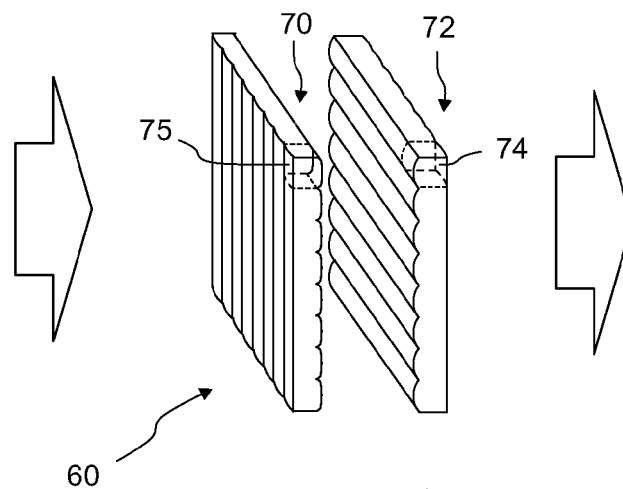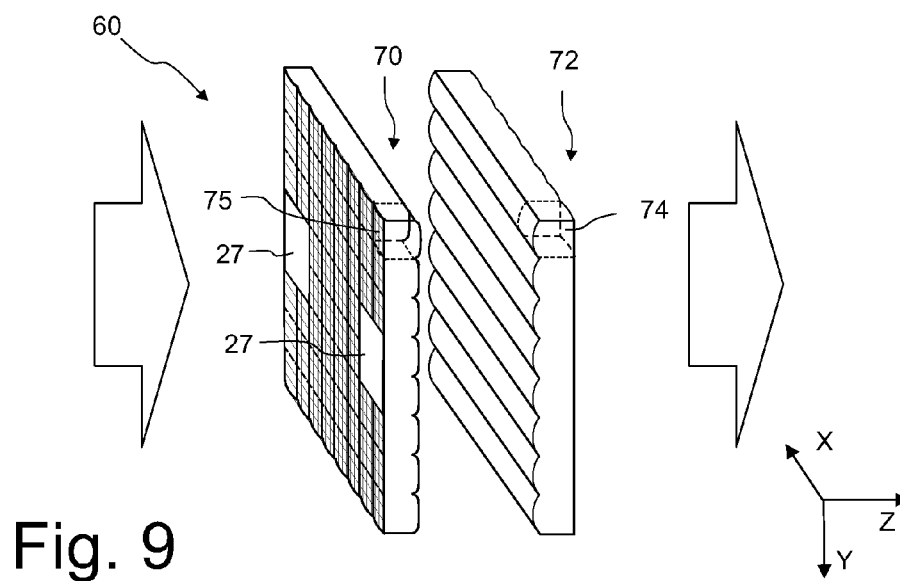
Fig. 10

Fig. 11a   Fig. 11b

Fig. 12

Fig. 14
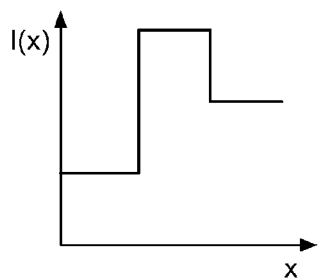
Fig. 13

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20a   Fig. 20b   Fig. 20c

Fig. 21

Fig. 22

Fig. 23

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OA

75

Fig. 24

54

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127

127

OA

75
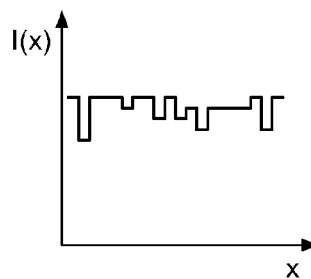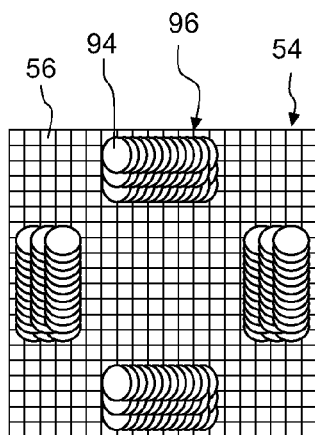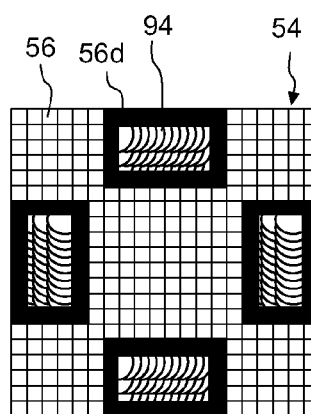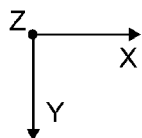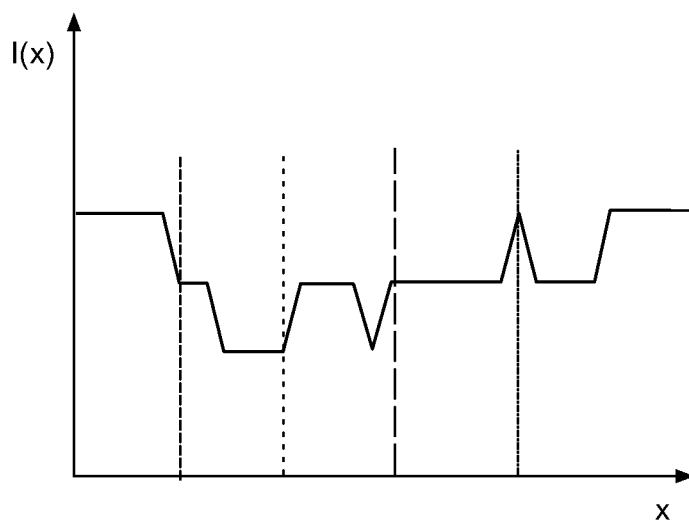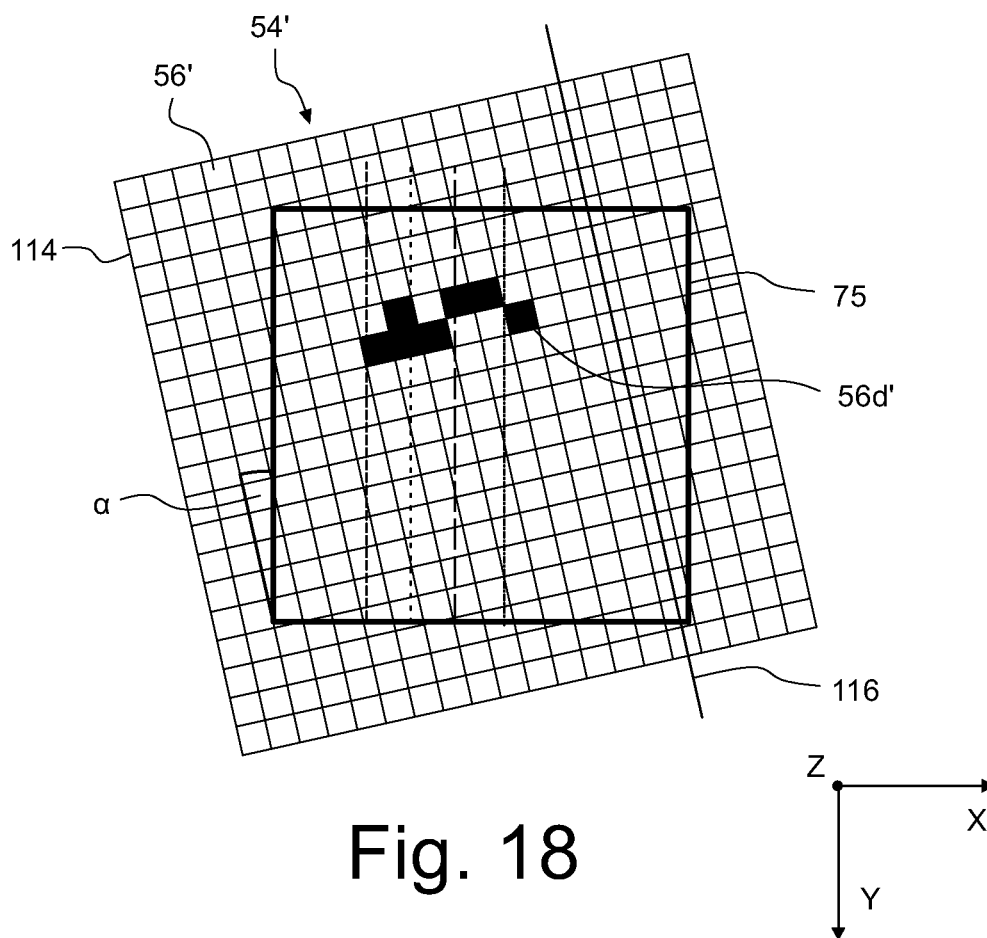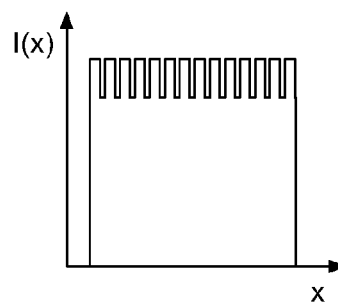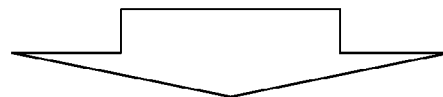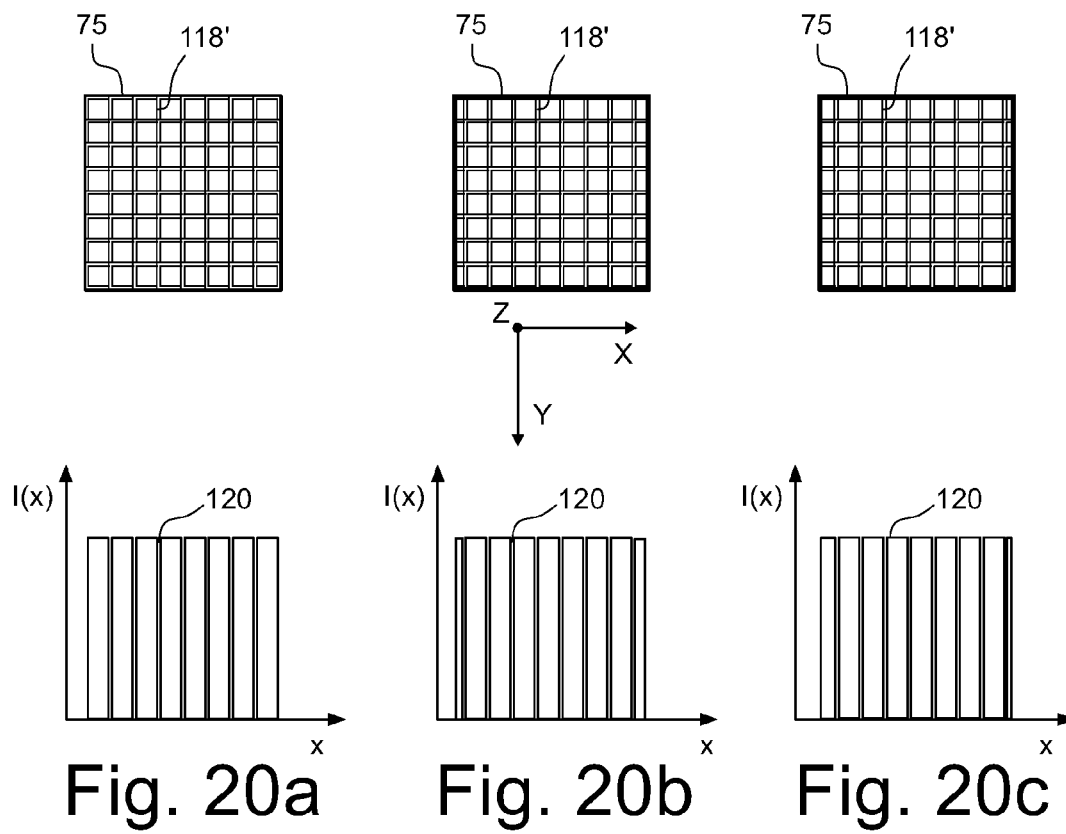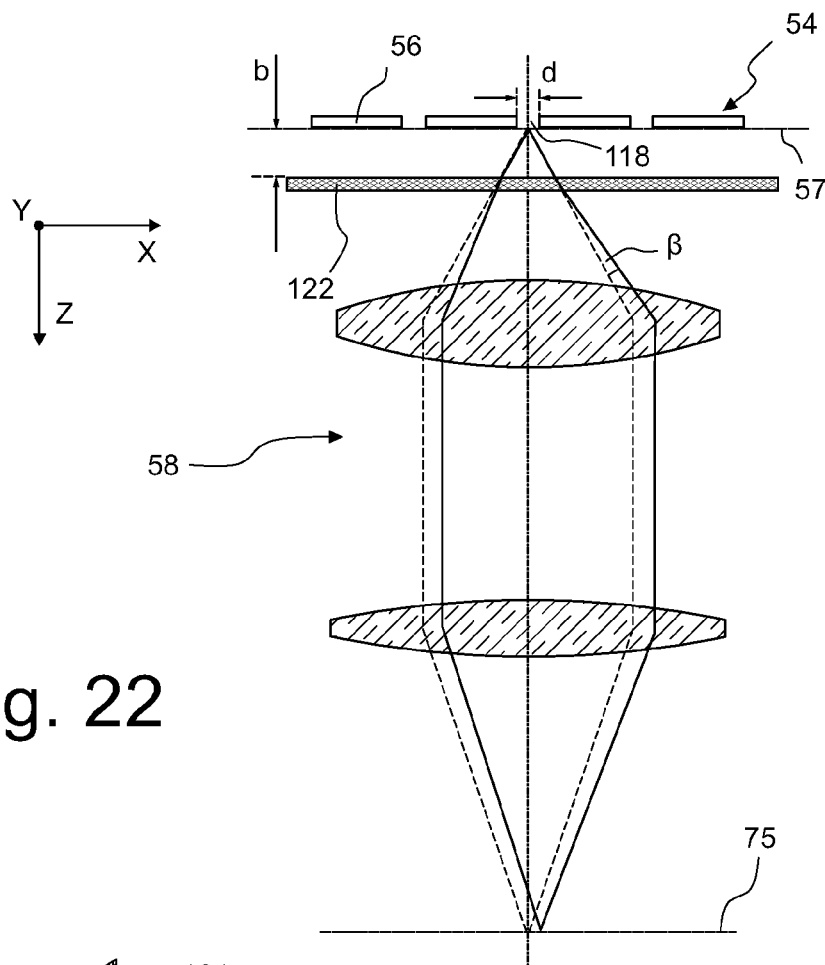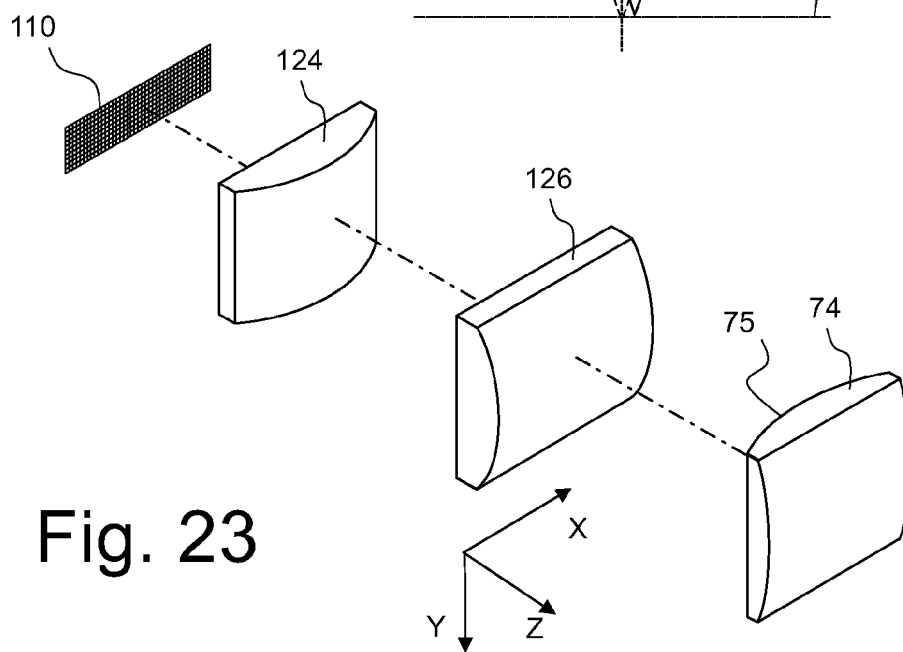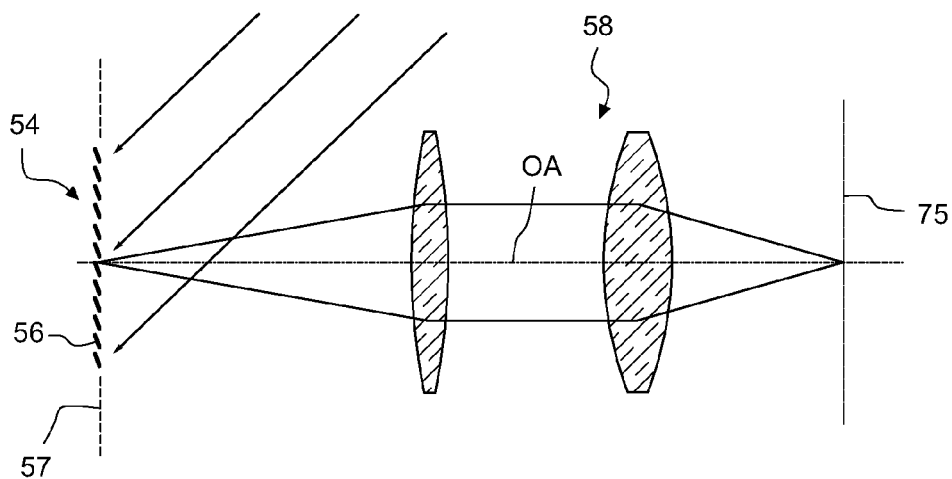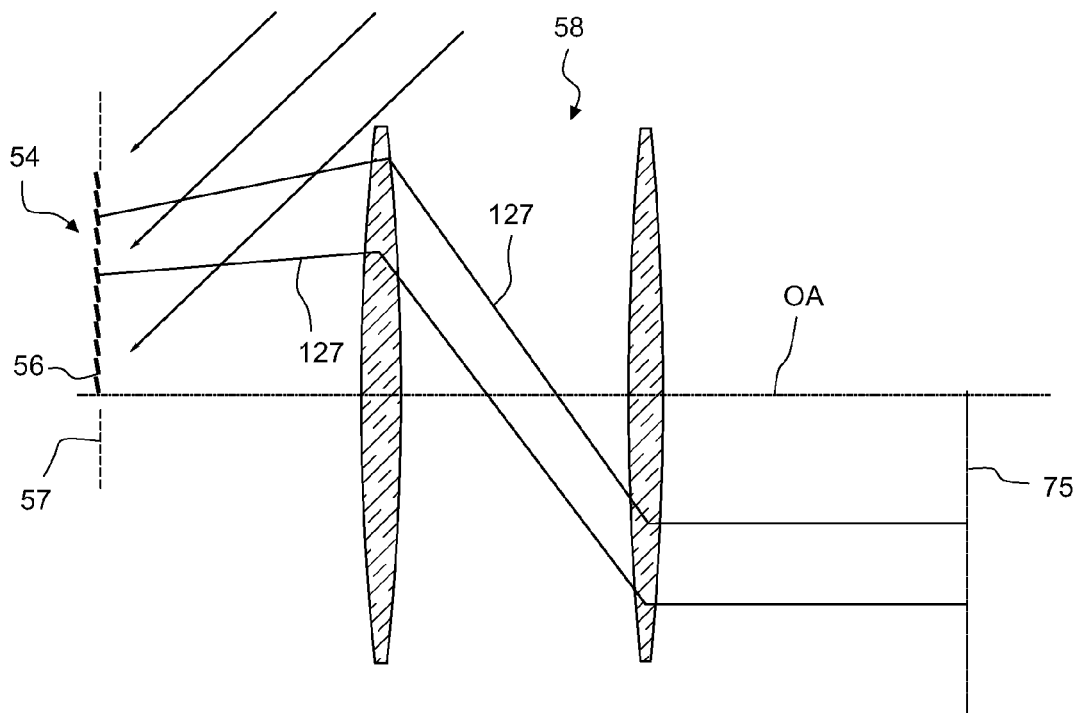
Fig. 25
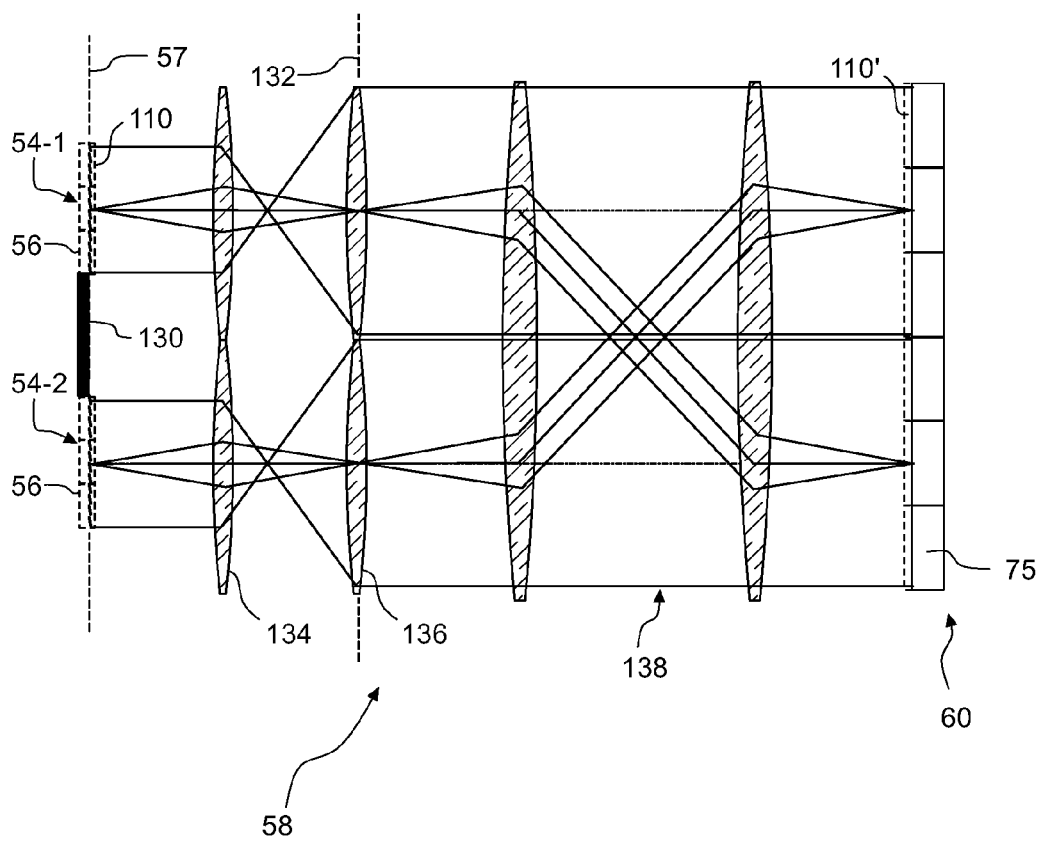
Fig. 26
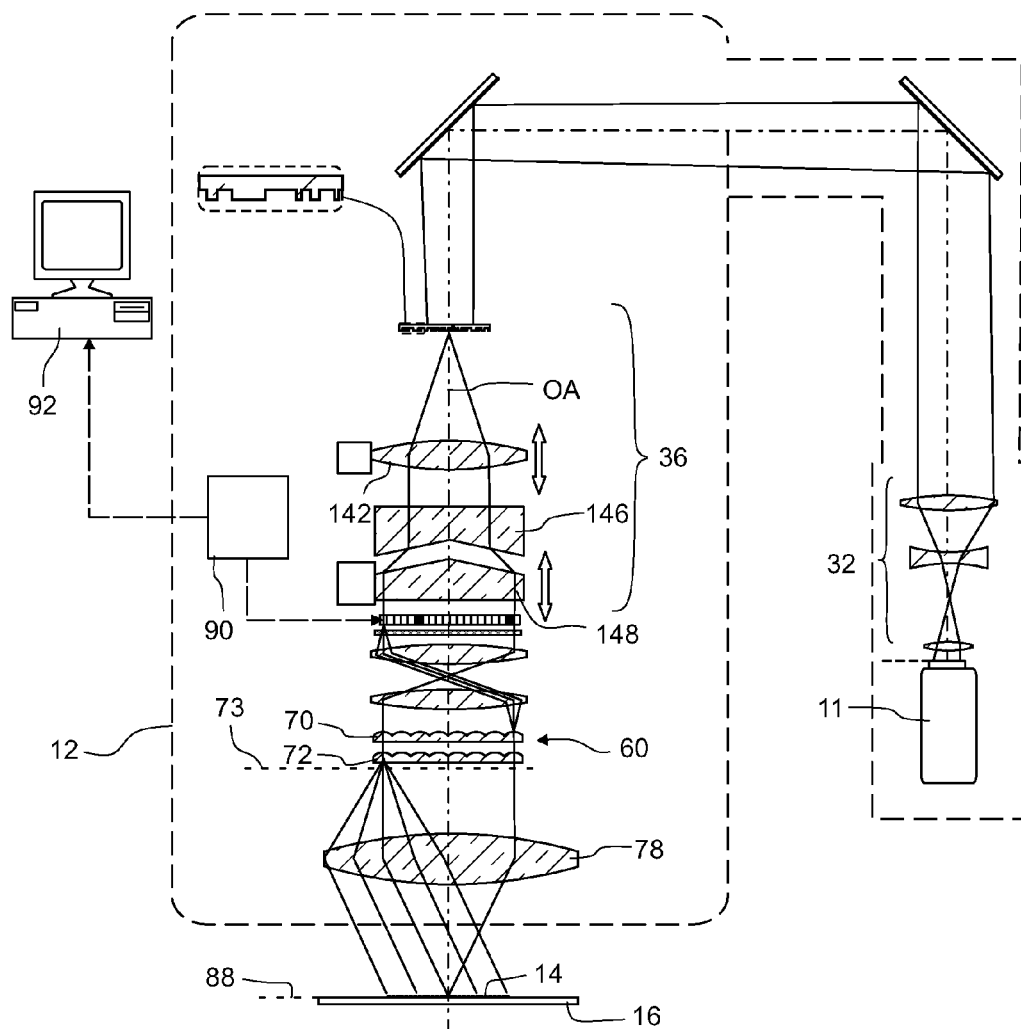
Fig. 27
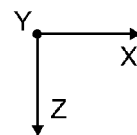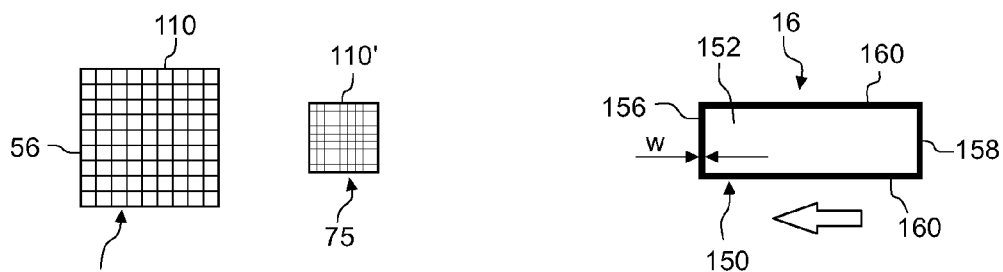
Fig. 28a
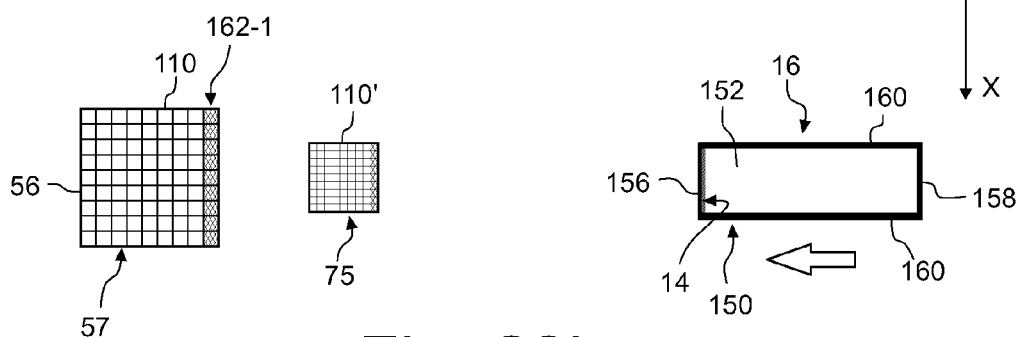
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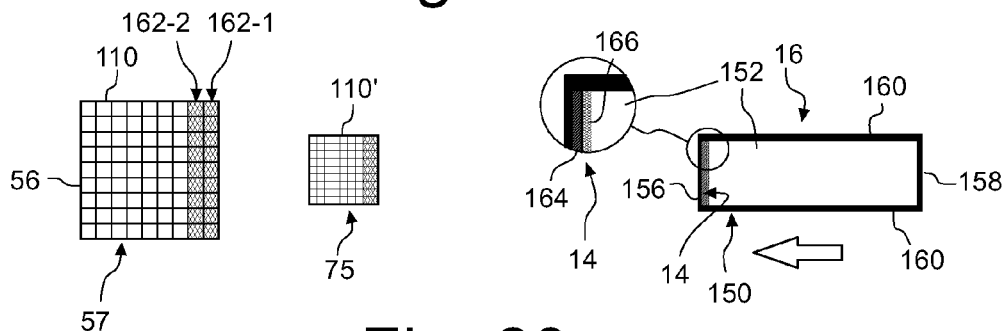
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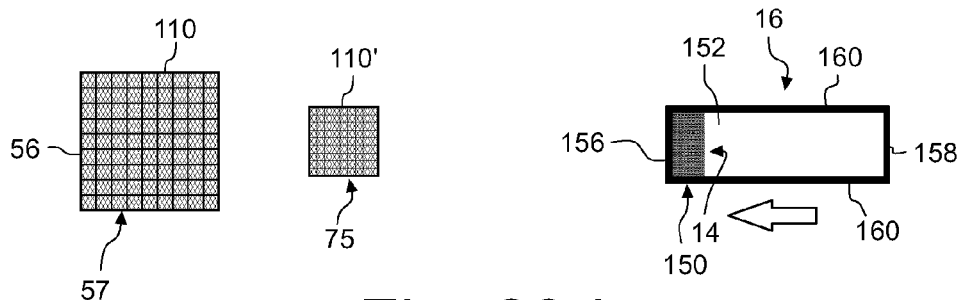
Fig. 28d
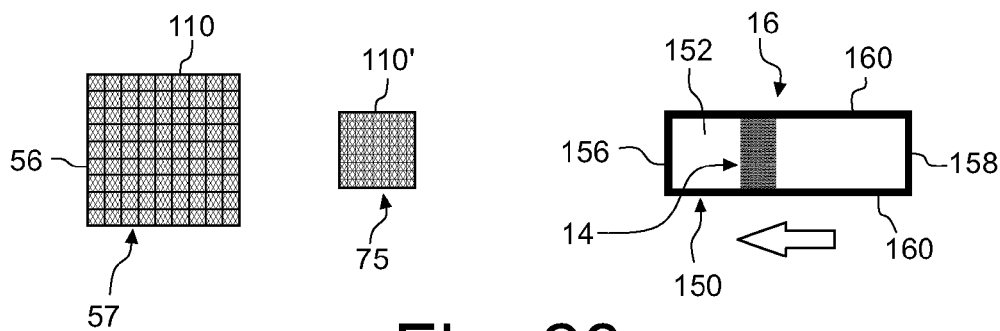
Fig. 28e

Fig. 28f

Fig. 28g

Fig. 28h

```
           ┌─────────────────┐
           │      Start       │
           └─────────────────┘
                    │
                    ▼
     ┌───────────────────────────────┐
     │ Illuminating a spatial light modulator │──── S1
     │    having a light exit surface         │
     └───────────────────────────────┘
                    │
                    ▼
     ┌───────────────────────────────┐
     │ Producing a light pattern in an object area │──── S2
     │      on the light exit surface              │
     └───────────────────────────────┘
                    │
                    ▼
     ┌───────────────────────────────┐
     │ Forming an intermediate image of the light  │
     │ pattern on a light entrance facet of an optical │──── S3
     │ integrator and a final image on a mask      │
     └───────────────────────────────┘
                    │
                    ▼
     ┌───────────────────────────────┐
     │ While the mask moves along a scan           │
     │ direction, changing the light pattern on the │
     │ object area so that a length of the final image │
     │ along the scan direction gradually increases │──── S3
     │ at the beginning of a scan cycle and         │
     │ gradually decreases at the end of the scan   │
     │                cycle                          │
     └───────────────────────────────┘
                    │
                    ▼
           ┌─────────────────┐
           │       End        │
           └─────────────────┘
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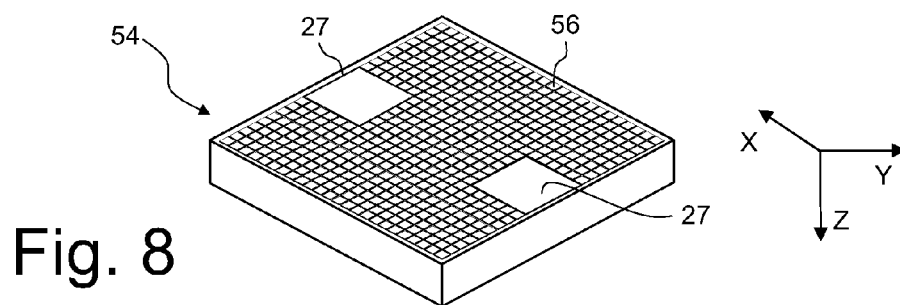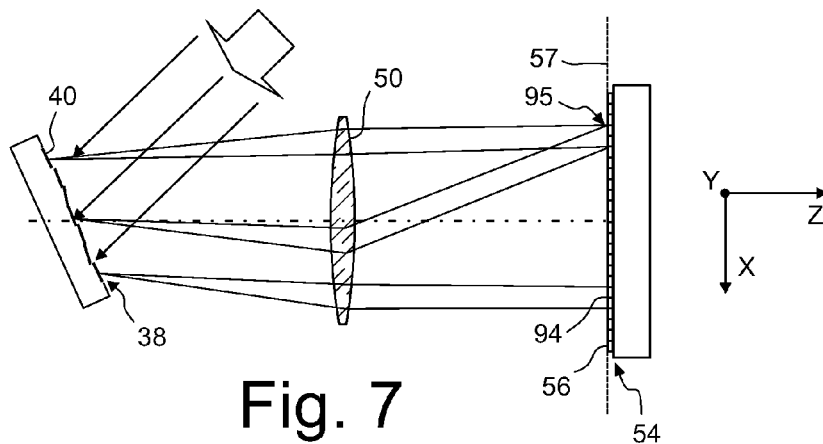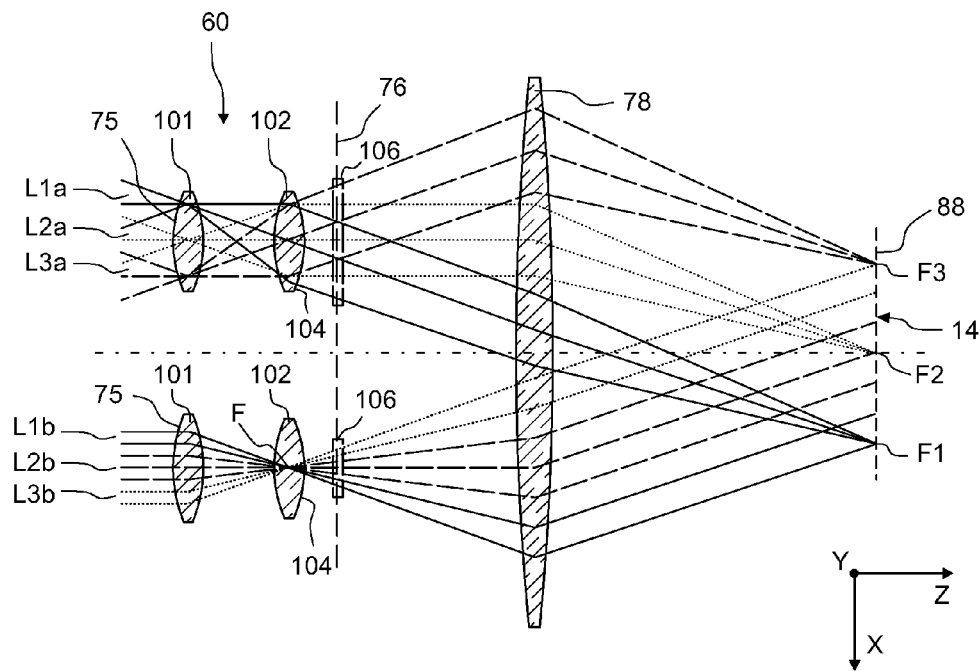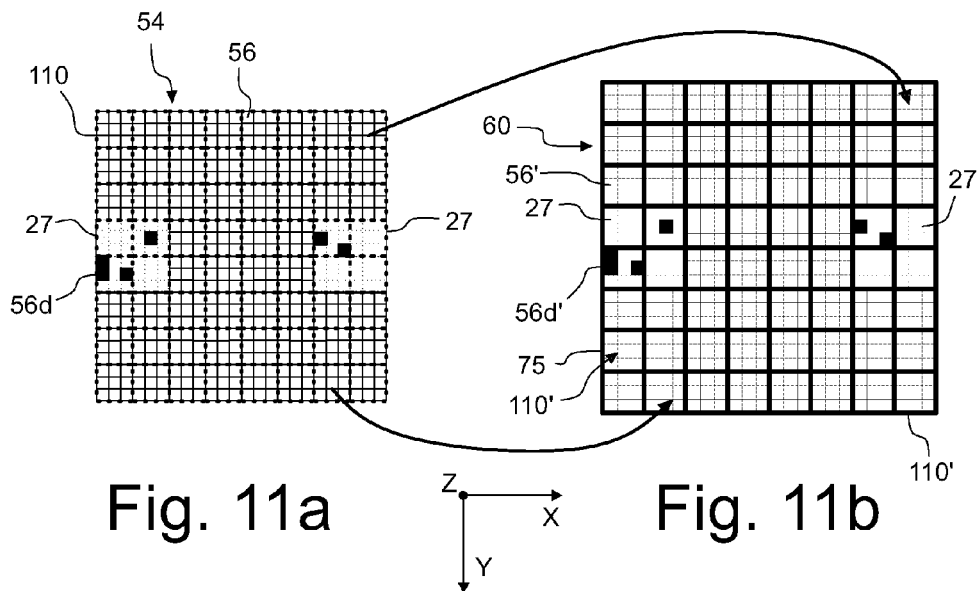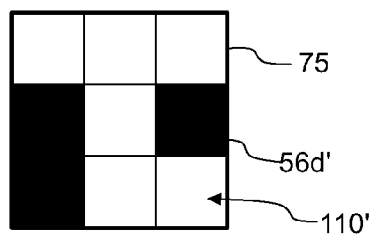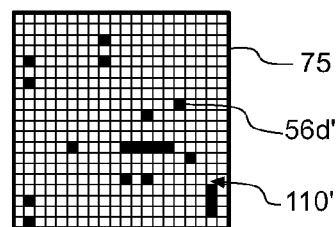
Fig. 29

ILLUMINATION SYSTEM OF A MICROLITHOGRAPHIC PROJECTION EXPOSURE APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims benefit under 35 USC 119 of European Application Nos. 13194135.3, filed Nov. 22, 2013 and 14155685.2, filed Feb. 19, 2014. The contents of both of these applications are hereby incorporated by reference in its entirety.

FIELD

The disclosure generally relates to illumination systems for illuminating a mask in a microlithographic exposure apparatus, and in particular to such systems including an optical integrator configured to produce a plurality of secondary light sources in a pupil plane. The disclosure also relates to a method of operating such illumination systems.

BACKGROUND

Microlithography (also referred to as photolithography or simply lithography) is a technology for the fabrication of integrated circuits, liquid crystal displays and other micro-structured devices. The process of microlithography, in conjunction with the process of etching, is used to pattern features in thin film stacks that have been formed on a substrate, for example a silicon wafer. At each layer of the fabrication, the wafer is first coated with a photoresist which is a material that is sensitive to radiation, such as deep ultraviolet (DUV) or vacuum ultraviolet (VUV) light. Next, the wafer with the photoresist on top is exposed to projection light in a projection exposure apparatus. The apparatus projects a mask containing a pattern onto the photoresist so that the latter is only exposed at certain locations which are determined by the mask pattern. After the exposure the photoresist is developed to produce an image corresponding to the mask pattern. Then an etch process transfers the pattern into the thin film stacks on the wafer. Finally, the photoresist is removed. Repetition of this process with different masks results in a multi-layered microstructured component.

A projection exposure apparatus typically includes a light source, an illumination system that illuminates the mask with projection light produced by the light source, a mask stage for aligning the mask, a projection objective and a wafer alignment stage for aligning the wafer coated with the photoresist. The illumination system illuminates a field on the mask that may have the shape of a rectangular or curved slit, for example.

In current projection exposure apparatus a distinction can be made between two different types of apparatus. In one type each target portion on the wafer is irradiated by exposing the entire mask pattern onto the target portion in one go. Such an apparatus is commonly referred to as a wafer stepper. In the other type of apparatus, which is commonly referred to as a step-and-scan apparatus or scanner, each target portion is irradiated by progressively scanning the mask pattern under the projection beam along a scan direction while synchronously moving the substrate parallel or anti-parallel to this direction. The ratio of the velocity of the wafer and the velocity of the mask is equal to the magnification of the projection objective, which is usually smaller than 1, for example 1:4.

It is to be understood that the term "mask" (or reticle) is to be interpreted broadly as a patterning mechanism. Commonly used masks contain opaque or reflective patterns and may be of the binary, alternating phase-shift, attenuated phase-shift or various hybrid mask type, for example. However, there are also active masks, e.g. masks realized as a programmable mirror array. Also programmable LCD arrays may be used as active masks.
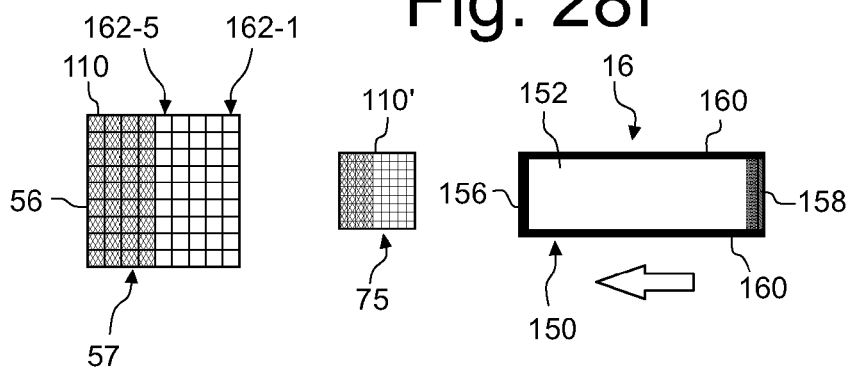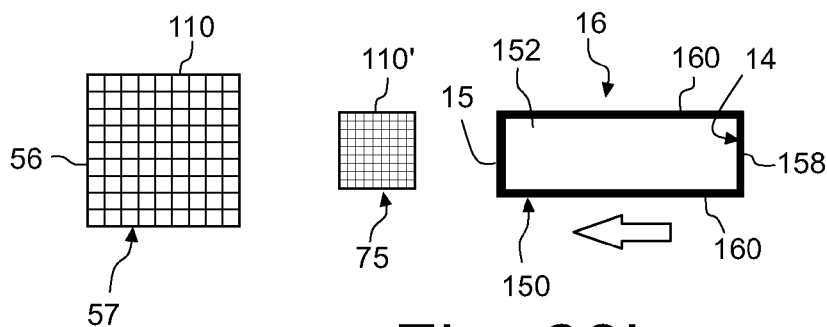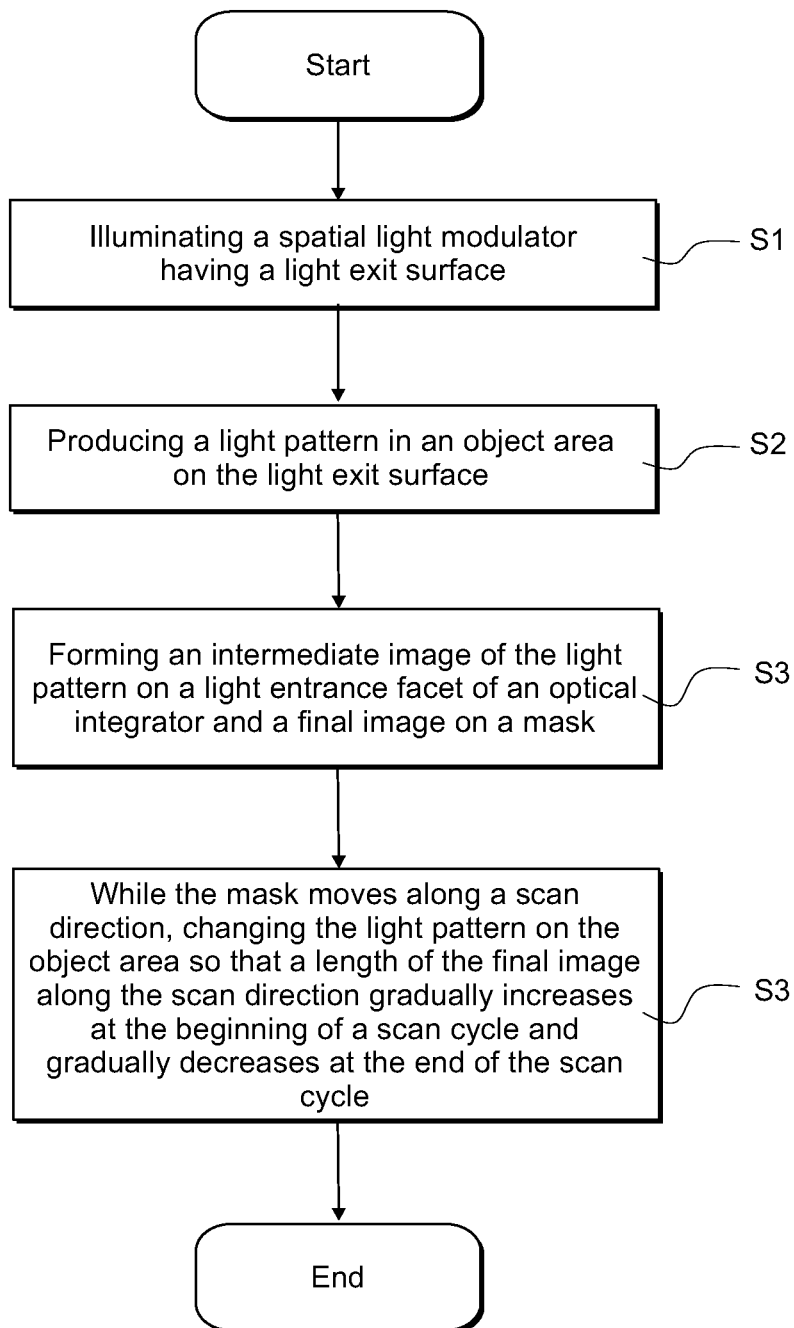
As the technology for manufacturing microstructured devices advances, there are ever increasing demands also on the illumination system. Ideally, the illumination system illuminates each point of the illumination field on the mask with projection light having a well defined spatial and angular irradiance distribution. The term angular irradiance distribution describes how the total light energy of a light bundle, which converges towards a particular point in the mask plane, is distributed among the various directions of the rays that constitute the light bundle.

The angular irradiance distribution of the projection light impinging on the mask is usually adapted to the kind of pattern to be projected onto the photoresist. Often the angular irradiance distribution depends on the size, orientation and pitch of the features contained in the pattern. The most commonly used angular irradiance distributions of projection light are referred to as conventional, annular, dipole and quadrupole illumination settings. These terms refer to the irradiance distribution in a pupil plane of the illumination system. With an annular illumination setting, for example, only an annular region is illuminated in the pupil plane. Thus there is only a small range of angles present in the angular irradiance distribution of the projection light, and all light rays impinge obliquely with similar angles onto the mask.

Different mechanisms are known in the art to modify the angular irradiance distribution of the projection light in the mask plane so as to achieve the desired illumination setting. In the simplest case a stop (diaphragm) including one or more apertures is positioned in a pupil plane of the illumination system. Since locations in a pupil plane translate into angles in a Fourier related field plane such as the mask plane, the size, shape and location of the aperture(s) in the pupil plane determines the angular irradiance distributions in the mask plane. However, any change of the illumination setting involves a replacement of the stop. This makes it difficult to finely adjust the illumination setting, because this would involve a very large number of stops that have aperture(s) with slightly different sizes, shapes or locations. Furthermore, the use of stops inevitably results in light losses and thus in a reduced throughput of the apparatus.

Many common illumination systems therefore include adjustable elements that make it possible, at least to a certain extent, to continuously vary the illumination of the pupil plane. Many illumination systems use an exchangeable diffractive optical element to produce a desired spatial irradiance distribution in the pupil plane. If zoom optics and a pair of axicon elements are provided between the diffractive optical element and the pupil plane, it is possible to adjust this spatial irradiance distribution.

Recently it has been proposed to use mirror arrays that illuminate the pupil plane. In EP 1 262 836 A1 the mirror array is realized as a micro-electromechanical system (MEMS) including more than 1000 microscopic mirrors. Each of the mirrors can be tilted in two different planes perpendicular to each other. Thus radiation incident on such a mirror device can be reflected into (substantially) any desired direction of a hemisphere. A condenser lens arranged between the mirror array and the pupil plane translates the reflection angles produced by the mirrors into locations in the pupil plane. This known illumination system makes it possible to illuminate the pupil plane with a plurality of spots,

wherein each spot is associated with one particular microscopic mirror and is freely movable across the pupil plane by tilting this mirror.

Similar illumination systems are known from US 2006/0087634 A1, U.S. Pat. No. 7,061,582 B2, WO 2005/026843 A2 and WO 2010/006687 A1. US 2010/0157269 A1 discloses an illumination system in which an array of micromirrors is directly imaged on the mask.

As mentioned further above, it is usually desired to illuminate, at least after scan integration, all points on the mask with the same irradiance and angular irradiance distribution. If points on the mask are illuminated with different irradiances, this usually results in undesired variations of the critical dimension (CD) on wafer level. For example, in the presence of irradiance variations the image of a line having a uniform width on the light sensitive surface may also have irradiance variations along its length. Because of the fixed exposure threshold of the resist, such irradiance variations directly translate into widths variations of a structure that shall be defined by the image of the line.

If the angular irradiance distribution varies over the illumination field on the mask, this also has a negative impact on the quality of the image that is produced on the light sensitive surface. For example, if the angular irradiance distribution is not perfectly balanced, i.e more light impinges from one side on a mask point than from the opposite side, the conjugate image point on the light sensitive surface will be laterally shifted if the light sensitive surface is not perfectly arranged in the focal plane of the projection objective. For modifying the spatial irradiance distribution in the illumination field U.S. Pat. No. 6,404,499 A and US 2006/0244941 A1 propose mechanical devices that include two opposing arrays of opaque finger-like stop elements that are arranged side by side and aligned parallel to the scan direction. Each pair of mutually opposing stop elements can be displaced along the scan direction so that the distance between the opposing ends of the stop elements is varied. If this device is arranged in a field plane of the illumination system that is imaged by an objective on the mask, it is possible to produce a slit-shaped illumination field whose width along the scan direction may vary along the cross-scan direction. Since the irradiance is integrated during each scan cycle, the integrated irradiance (sometimes also referred to as illumination close) can be finely adjusted for a plurality of cross-scan positions in the illumination field.

However, these devices are mechanically very complex and expensive. This is also due to the fact that these devices have to be arranged in or very close to a field plane in which usually the blades of a movable field stop is arranged.

Adjusting the angular irradiance distribution in a field dependent manner is more difficult. This is mainly because the spatial irradiance distribution is only a function of the spatial coordinates x, y, whereas the angular irradiance distribution also depends on the direction of incidence given by a pair of angles α, β.

WO 2012/100791 A1 discloses an illumination system in which a first mirror array is used to produce a desired irradiance distribution in the pupil plane of the illumination system. In close proximity to the pupil plane an optical integrator is arranged that has a plurality of light entrance facets. Thus images of the light entrance facets are superimposed on the mask. The light spots produced by the mirror array have an area that is at least five times smaller than the total area of the light entrance facets. Thus it is possible to produce variable light patterns on the light entrance facets. In this manner different angular irradiance distributions can be produced on different portions of the illumination field. It is thus possible,

for example, to produce an X dipole and a Y dipole illumination setting at a given time in the illumination field.

In order to ensure that the portions with different illumination settings are sharply delimited, it is proposed to use a second mirror array configured as a digital mirror device (DMD). This second mirror array is illuminated by the first mirror array and is imaged on the light entrance facets by an objective. By bringing larger groups of micromirrors of the second mirror array in an "off"-state, it is possible to produce irradiance distributions on the light entrance facets that have sharp boundaries.

However, it turned out that it is difficult to produce so many and so small freely movable light spots with the first mirror array. Furthermore, this prior art illumination system is mainly concerned with producing completely different illumination settings at different portions in the illumination field. For that reason the light entrance facets are usually not completely, but only partially illuminated.

In prior art illumination systems of the scanner type an adjustable field stop including movable blades opens and closes the slit-like illumination field at the beginning and the end of each scan cycle, respectively. This ensures that only the desired portions on the mask are projected on the light sensitive surface. The adjustable field stop has to perform its task reliably and with the highest accuracy. For that reason it is usually a mechanically complex and expensive device. Furthermore, the blades of the adjustable field stop have to be imaged on the mask with the help of a large objective. This objective involves a lot of space and significantly adds to the total manufacturing costs of the illumination system. WO 2010/006687 A1 discloses an illumination system that is similar to the one disclosed in WO 2012/100791 A1 that has been mentioned above. Here the variable light patterns on the light entrance facets are not used to modify a field dependence of the angular light distribution, but to take over the function of the movable blades of the adjustable field stop. However, also in this prior art illumination system very small light spots have to be produced on the light entrance facets. These spots are produced by a mirror array at positions that can be varied by changing a deflection angle produced by the mirrors.

SUMMARY

It is therefore an object of the present disclosure to provide an illumination system of a microlithographic projection exposure apparatus which overcomes at least some of the disadvantages associated with prior art adjustable field stops.

In accordance with the present disclosure this object is achieved by an illumination system that is configured to illuminate a mask moving along a scan direction in a mask plane. The illumination system includes an optical integrator configured to produce a plurality of secondary light sources located in a pupil plane of the illumination system. The optical integrator includes a plurality of light entrance facets each being associated with one of the secondary light sources. Images of the light entrance facets at least substantially superimpose in the mask plane. The illumination system further includes a spatial light modulator that has a light exit surface and is configured to transmit or to reflect impinging projection light in a spatially resolved manner. A pupil forming unit is configured to direct projection light on the spatial light modulator. An objective images the light exit surface of the spatial light modulator onto the light entrance facets of the optical integrator so that an image of an object area on the light exit surface completely coincides with one of the light entrance facets. In accordance with the present disclosure a control unit is configured to control the spatial light modula-

tor such that along the scan direction a length of an image, which is formed on the mask from a light pattern in the object area, gradually increases at a beginning of a scan cycle and gradually decreases at the end of the scan cycle.

The disclosure is based on the perception that light patterns on the light entrance facets of the optical integrator are imaged on the mask. By modifying these light patterns it is thus possible to vary the size of the illumination field on the mask. For modifying the light patterns a spatial light modulator is used that may be configured as a digital mirror device (DMD) or a plurality of such devices. Thus the function of prior art adjustable field stops is taken over by a suitable control of the spatial light modulator. The macroscopic movements of the blades in prior art adjustable field stops is replaced, for example, by minute tilt movements of a huge number of digital micromirrors.

In this manner that mechanically complex and expensive adjustable field stop can be dispensed with. In accordance with the disclosure there is no need for a field plane (i.e. a plane that is optically conjugate to the mask) between the light entrance facets and the mask. Thus also the bulky and expensive objective that images the movable blades on the mask is not required.

In comparison to this bulky objective, the additional objective that images the light exit surface of the spatial light modulator on the light entrance facets of the optical integrator has a much smaller size and complexity. This is because the light passing through this objective is usually almost parallel, which results in a small numerical aperture. Furthermore, the size of the light exit surface and of the optical integrator is usually smaller than the size of the illumination field on the mask. Thus the two quantities that have the main impact on the size and complexity of objectives, namely numerical aperture and field size, are small as compared to objectives that image the blades on the mask. The objective that images the light exit surface of the spatial light modulator on the light entrance facets can therefore be realized with very few and preferably spherical lenses.

If compared to the prior art illumination system disclosed in WO 2010/006687 A1, the main benefit of the illumination system in accordance with the present disclosure is the use of a spatial light modulator having a light exit surface that is imaged on the light entrance facets. For that reason it is not necessary to move tiny spots to arbitrary positions on the light entrance facets, as this is the case in the prior art illumination system. Instead, the light modulator only needs to produce variable light patterns on its light exit surface. As will be explained below in further detail, this can be accomplished with relatively simple digital devices such as digital mirror devices (DMD) or LCD panels.

With the spatial light modulator it is also possible to dispense with mechanical complex devices that are used in prior art illumination systems to adjust the spatial irradiance distribution along the cross-scan direction.

Since all components of the illumination system may be purely reflective, the disclosure can principally also be used in EUV illumination systems.

The pupil forming unit may include a diffractive optical element for defining an irradiance distribution on the spatial light modulator that is imaged on the light entrance facets of the optical integrator. For fine adjustments of this irradiance distribution zoom optics and/or a pair of axicon elements may be arranged in the light path between the diffractive optical element and the spatial light modulator.

A more flexible setting of the irradiance distribution on the spatial light modulator is possible if the pupil forming unit includes a first beam deflection array of first reflective or

transparent beam deflection elements. Each beam deflection element is configured to illuminate a spot on the spatial light modulator at a position that is variable by changing a deflection angle produced by the beam deflection element.

The spatial light modulator may be of the transparent or the reflective type and may include an array of elements that can be used to attenuate, completely block or deflect impinging light. For example, the spatial light modulator may be configured as an LCD panel including a two dimensional array of LCD cells whose optical activity can be controlled individually by the control unit. In modulators of the transparent type the object area is usually illuminated from its back side.

In one embodiment the spatial light modulator includes a second beam deflection array of second reflective or transparent beam deflection elements. Each second beam deflection element is capable to be in an "on"-state, in which it directs impinging light towards the optical integrator, and in an "off"-state, in which it directs impinging light elsewhere, for example on a light absorbing surface. Such a second beam deflection array may be configured as a digital mirror device which may include millions of individual micromirrors.

Generally the larger the number of second beam deflection elements arranged in the object area is, the better is the spatial resolution that can be used for changing the irradiance distribution on the mask during the scan cycle. Preferably at least 10, and even more preferably at least 50, second beam deflection elements are arranged in the object area.

In one embodiment centers of adjacent second beam deflection elements arranged in the object area are aligned along a straight line. An image of the straight line forms an angle α to a boundary line of the one of the light entrance facets, wherein α is distinct from $m \cdot 45°$ with $m=0, 1, 2, 3, \ldots$ . . With such an oblique arrangement of the second beam deflection array with respect to the light entrance facets the distance is reduced between cross-scan positions in the illumination field at which the attenuation is different.

For example, the boundaries of the second beam deflection elements may be arranged in a first rectangular grid, and boundaries of the light entrance facets may be arranged in a second rectangular grid. Then the image of the first rectangular grid formed on the light entrance facets forms the angle α to the second rectangular grid.

If the mask moves along a scan direction while it is illuminated by the illumination system, the irradiance and angular irradiance distribution at a point on the mask is obtained by integrating the irradiances and angular irradiance distributions during the scan cycle, i.e. while the point on the mask moves through the illumination field. If it is desired to finely adjust the field dependence of the irradiance and angular irradiance distribution, it may be sufficient to provide only a few second beam deflection elements along the scan direction, but a larger number of second beam deflection elements along the cross-scan direction. This usually implies that a length of the object area along the first direction should be larger than a length of the object area along a second direction which is orthogonal to the first direction. Then the objective should be an anamorphotic objective having a magnification M with |M| being smaller along the first direction than along the second direction. The anamorphotic objective ensures that the image of the elongated object area is not elongated, but coincides with the (usually square) shape of the light entrance facets.

Instead of or in addition to using an anamorphotic objective, it is possible to use an anamorphotic condenser having a front focal plane which coincides with the pupil plane and having a focal length f being shorter along the first direction than along the second direction.

Generally it is preferred if the second beam deflection elements are arranged in an object plane of the objective that is parallel to a plane in which the light entrance facets are arranged. This can be achieved if the second beam deflection elements are configured such that they produce in the "on"-state a deflection of impinging light by an angle distinct from zero. Additionally or alternatively the objective may be non-telecentric on an object side and telecentric on an image side.

Generally the light spots produced by the first beam deflection array on the object area will be larger than the object area. However, the disclosure may also be used if the spots are smaller than the object area.

Since gaps between second beam deflection elements are, via the light entrance facets of the optical integrator, eventually imaged on the illumination field, measures should be taken that this does not compromise the uniformity of the spatial and angular irradiance distribution in the illumination field. To this end a scattering plate may be arranged in a light path between the optical light modulator and the mask plane, preferably close to a field plane. The scattering plate blurs the irradiance distribution on the light entrance facets and thus ensures that no dark lines occur in the illumination field.

If the light exit surface of the optical light modulator includes groups of object areas that are separated by areas that are not imaged on the light entrance facets, the objective may be configured to combine images of the active object areas so that the images of the object areas abut on the light entrance facets.

In particular the objective may include a first array of first optical elements, wherein each first optical element forms a magnified image of one of the object areas in an intermediate image plane, and imaging optics that image the intermediate image plane on the light entrance facets.

Usually it is desired that the image, which is formed on the mask from the light pattern in the object area, has a length along a cross-scan direction, which is perpendicular to the scan direction, that remains constant during the scan cycle. Then the illumination field changes its size only along the scan direction at the beginning and the end of each scan cycle.

In one embodiment the control unit is configured to control the spatial light modulator such that rows of adjacent second beam deflection elements are simultaneously brought from the "off" state into the "on" state and vice versa during the scan cycle. Then the length of the illumination field along the scan direction mask increases or decreases uniformly along the cross-scan direction, i.e. the illumination field changes by the addition or deletion of straight or curved narrow stripes.

Subject of the disclosure is also a microlithographic projection exposure apparatus including the illumination system in accordance with the present disclosure and a mask. The mask contains a light absorbing stripe extending perpendicular to the scan direction and having a width along the scan direction which is greater than or equal to a length along the scan direction of an image of one of the second beam deflection elements formed on the mask plane. Then a narrow stripe being an image of one row of second beam deflection elements can be illuminated first on the light absorbing stripe. As the mask moves further along the scan direction, the illuminated stripe enters a central area of the mask where the features to be illuminated are arranged. In this manner the length of the illumination field along the scan direction changes continuously in spite of the discrete character of the beam deflection elements. The term "light absorbing stripe" is to be understood broadly in the sense that the stripe may also reflect the light to a light absorbing element arranged elsewhere.

Subject of the disclosure is also an illumination system of a projection exposure apparatus including a spatial light

modulator that is configured to transmit or to reflect impinging light in a spatially resolved manner, a pupil forming unit configured to direct light on the spatial light modulator, and an optical integrator configured to produce a plurality of secondary light sources located in a pupil plane. The optical integrator includes a plurality of light entrance facets each being associated with one of the secondary light sources. An objective images a light exit surface of the spatial light modulator on the light entrance facets of the optical integrator. In accordance with the present disclosure there is no plane that is optically conjugate to the mask between the light entrance facets and the mask.

This illumination system thus dispenses with a field stop plane in which an adjustable field stop including moving blades is arranged. The function of the adjustable field stop is taken over by the spatial light modulator.

To this end the illumination system may include a control unit that is configured to control the spatial light modulator such that along the scan direction a length of an image, which is formed on the mask from a light pattern in an object area of the spatial light modulator, gradually increases at a beginning of a scan cycle and gradually decreases at the end of the scan cycle.

Subject of the disclosure is also a method of operating an illumination system of a microlithographic projection exposure apparatus, including the following steps:

a) illuminating a spatial light modulator having a light exit surface;

b) producing a light pattern in an object area on the light exit surface;

c) forming an intermediate image of the light pattern on a light entrance facet of an optical integrator and a final image on a mask;

d) while the mask moves along a scan direction, changing the light pattern on the object area so that a length of the final image along the scan direction gradually increases at the beginning of a scan cycle and gradually decreases at the end of the scan cycle.

The final image on the mask may have a length along a cross-scan direction, which is perpendicular to the scan direction, that remains constant during the scan cycle.

Between the light entrance facets and the mask there may be no plane that is optically conjugate to the mask.

The spatial light modulator may be illuminated by a pupil forming unit that includes a first beam deflection array of first reflective or transparent beam deflection elements. Each beam deflection element illuminates a spot on the spatial light modulator at a position that is variable by changing a deflection angle produced by the beam deflection element.

The spatial light modulator may include a second beam deflection array of second reflective or transparent beam deflection elements. Some second beam deflection element may then be switched from an "off" state into an "on" state at the beginning of the scan cycle, and some second beam deflection elements may then be switched from the "on" state to the "off" state at the end of the scan cycle.

Rows of adjacent second beam deflection elements may be simultaneously brought from the "off" state into the "on" state at the beginning of the scan cycle, and different rows of adjacent second beam deflection elements may be switched from the "on" state to the "off" state at the end of the scan cycle.

The light exit surface of the optical light modulator may include groups of object areas that are separated by areas that are not imaged on the light entrance facets. An objective combines images of the object areas so that the images of the object areas abut on the optical integrator.

Such an objective may include a first array of first optical elements, wherein each first optical element forms a magnified image of one of the groups in an intermediate image plane. Imaging optics image the intermediate image plane on the light entrance facets.

DEFINITIONS

The term "light" is used herein to denote any electromagnetic radiation, in particular visible light, UV, DUV, VUV and EUV light and X-rays.

The term "light ray" is used herein to denote light whose path of propagation can be described by a line.

The term "light bundle" is used herein to denote a plurality of light rays that have a common origin in a field plane.

The term "light beam" is used herein to denote all light that passes through a particular lens or another optical element.

The term "position" is used herein to denote the location of a reference point of a body in the three-dimensional space. The position is usually indicated by a set of three Cartesian coordinates. The orientation and the position therefore fully describe the placement of a body in the three-dimensional space.

The term "surface" is used herein to denote any plane or curved surface in the three-dimensional space. The surface may be part of a body or may be completely separated therefrom, as it is usually the case with a field or a pupil plane.

The term "field plane" is used herein to denote the mask plane or any other plane that is optically conjugate to the mask plane.

The term "pupil plane" is a plane in which (at least approximately) a Fourier relationship is established to a field plane. Generally marginal rays passing through different points in the mask plane intersect in a pupil plane, and chief rays intersect the optical axis. As usual in the art, the term "pupil plane" is also used if it is in fact not a plane in the mathematical sense, but is slightly curved so that, in the strict sense, it should be referred to as pupil surface.

The term "uniform" is used herein to denote a property that does not depend on the position.

The term "optical raster element" is used herein to denote any optical element, for example a lens, a prism or a diffractive optical element, which is arranged, together with other identical or similar optical raster elements so that each optical raster element is associated with one of a plurality of adjacent optical channels.

The term "optical integrator" is used herein to denote an optical system that increases the product NA·a, wherein NA is the numerical aperture and a is the illumination field area.

The term "condenser" is used herein to denote an optical element or an optical system that establishes (at least approximately) a Fourier relationship between two planes, for example a field plane and a pupil plane.

The term "conjugate plane" is used herein to denote planes between which an imaging relationship is established. More information relating to the concept of conjugate planes are described in an essay E. Delano entitled: "First-order Design and the y, $\bar{y}$ Diagram", Applied Optics, 1963, vol. 2, no. 12, pages 1251-1256.

The term "field dependence" is used herein to denote any functional dependence of a physical quantity from the position in a field plane.

The term "spatial irradiance distribution" is used herein to denote how the total irradiance varies over a real or imaginary surface on which light impinges. Usually the spatial irradiance distribution can be described by a function $I_s(x, y)$, with x, y being spatial coordinates of a point on the surface.

The term "angular irradiance distribution" is used herein to denote how the irradiance of a light bundle varies depending on the angles of the light rays that constitute the light bundle. Usually the angular irradiance distribution can be described by a function $I_a(\alpha,\beta)$, with α, β being angular coordinates describing the directions of the light rays. If the angular irradiance distribution has a field dependence, I_a will be also a function of field coordinates, i.e. $I_a=I_a(\alpha, \beta,x,y)$. The field dependence of the angular irradiance distribution may be described by a set of expansion coefficients a_{ij} of a Taylor (or another suitable) expansion of $I_a(\alpha, \beta,x,y)$ in x, y.

The term "scan cycle" is used herein to denote a scanning process during which a complete die on the wafer or another support is exposed to projection light.

BRIEF DESCRIPTION OF THE DRAWINGS

Various features and advantages of the present disclosure may be more readily understood with reference to the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. 1 is a schematic perspective view of a projection exposure apparatus in accordance with one embodiment of the present disclosure;

FIG. 2 is an enlarged perspective view of the mask to be projected by the projection exposure apparatus shown in FIG. 1, illustrating various deficiencies of the angular irradiance distribution;

FIG. 3 is a meridional section through an illumination system being part of the apparatus shown in FIG. 1;

FIG. 4 is a perspective view of a first mirror array contained in the illumination system shown in FIG. 3;

FIG. 5 is a perspective view of a second mirror array contained in the illumination system shown in FIG. 3;

FIG. 6 is a perspective view of an optical integrator contained in the illumination system shown in FIG. 3;

FIG. 7 is a schematic meridional section through the first and the second mirror array shown in FIGS. 4 and 5;

FIG. 8 is a perspective view on the second mirror array shown in FIG. 5, but illuminated with two poles;

FIG. 9 is a perspective view of the optical integrator shown in FIG. 6, but illuminated with two poles;

FIG. 10 is a schematic meridional section through a portion of the illumination system in which only a mirror array, a condenser and an array of optical raster elements are shown;

FIGS. 11a and 11b are top views on the second mirror array and the optical integrator shown in FIG. 3;

FIG. 12 illustrates an irradiance distribution on a light entrance facet of the optical integrator;

FIG. 13 is a graph showing the scan integrated irradiance distribution along the X direction produced by the light entrance facet shown in FIG. 12;

FIG. 14 illustrates another irradiance distribution on a light entrance facet of the optical integrator;

FIG. 15 is a graph showing the scan integrated irradiance distribution along the X direction produced by the light entrance facet shown in FIG. 14;

FIG. 16 is a top view on the second mirror array on which a plurality of light spots produce an irradiance distribution;

FIG. 17 shows the second mirror array of FIG. 16, but with several of the micromirrors in an "off"-state;

FIG. 18 is a top view on the irradiance distribution on a single light entrance facet for an alternative embodiment;

FIG. 19 is a graph showing the scan integrated irradiance distribution along the X direction produced by the light entrance facet shown in FIG. 18;

FIGS. **20***a* to **20***c* illustrate images of micromirrors on a light entrance facet and the corresponding irradiance distribution on the mask;

FIG. **21** is a graph showing the total irradiance distribution that is obtained by superimposing the irradiance distributions shown in FIGS. **20***a* to **20***c;*

FIG. **22** is a schematic meridional section through an objective, which is contained in the illumination system shown in FIG. **3**, and an additional scattering plate;

FIG. **23** is a schematic perspective view on an object area on the second mirror array, an anamorphotic objective and an optical raster element of the optical integrator;

FIG. **24** is a schematic meridional section showing the second mirror array, the objective and a light entrance facet;

FIG. **25** shows a similar arrangement as in FIG. **24**, but with an off-axis arrangement of the micromirrors and the light entrance facets;

FIG. **26** is a meridional section through an embodiment in which groups of object areas are separated by a gap that is not imaged on the light entrance facets;

FIG. **27** is a meridional section through an illumination system according to another embodiment in which a diffractive optical element is used to define the irradiance distribution on an LCD panel used as spatial light modulator;

FIGS. **28***a* to **28***h* are top views on an object area of the spatial light modulator, on a light entrance facet and on the mask at various stages of a scan cycle;

FIG. **29** is a flow diagram that illustrates important method steps.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

I

General Construction of Projection Exposure Apparatus

FIG. **1** is a perspective and highly simplified view of a projection exposure apparatus **10** in accordance with the present disclosure. The apparatus **10** includes a light source **11** that may be realized as an excimer laser, for example. The light source **11** in this embodiment produces projection light having a center wavelength of 193 nm. Other wavelengths, for example 257 nm or 248 nm, are envisaged as well.

The apparatus **10** further includes an illumination system **12** which conditions the projection light provided by the light source **11** in a manner that will be explained below in further detail. The projection light emerging from the illumination system **12** illuminates an illumination field **14** on a mask **16**. The mask **16** contains a pattern **18** formed by a plurality of small features **19** that are schematically indicated in FIG. **1** as thin lines. The features **19** are surrounded by an opaque rim **150**, as this will be explained in further detail below with reference to FIGS. **28***a* to **28***h*. In this embodiment the illumination field **14** has the shape of a rectangle. However, other shapes of the illumination field **14**, for example a ring segment, are also contemplated.

A projection objective **20** including lenses L1 to L6 images the pattern **18** within the illumination field **14** onto a light sensitive layer **22**, for example a photoresist, which is supported by a substrate **24**. The substrate **24**, which may be formed by a silicon wafer, is arranged on a wafer stage (not shown) such that a top surface of the light sensitive layer **22** is precisely located in an image plane of the projection objective **20**. The mask **16** is positioned via a mask stage (not shown) in an object plane of the projection objective **20**. Since the latter

has a magnification β with $|\beta|<1$, a minified image **18'** of the pattern **18** within the illumination field **14** is projected onto the light sensitive layer **22**.

During the projection the mask **16** and the substrate **24** move along a scan direction which corresponds to the Y direction indicated in FIG. **1**. The illumination field **14** then scans over the mask **16** so that patterned areas larger than the illumination field **14** can be continuously imaged. The ratio between the velocities of the substrate **24** and the mask **16** is equal to the magnification β of the projection objective **20**. If the projection objective **20** does not invert the image ($\beta>0$), the mask **16** and the substrate **24** move along the same direction, as this is indicated in FIG. **1** by arrows A1 and A2. However, the present disclosure may also be used in stepper tools in which the mask **16** and the substrate **24** do not move during projection of the mask.

II

Field Dependent Angular Irradiance Distribution

FIG. **2** is an enlarged perspective view of the mask **16** containing another exemplary pattern **18**. For the sake of simplicity it is assumed that the pattern **18** includes only features **19** that extend along the Y direction. It is further assumed that the features **19** extending along the Y direction are best imaged on the light sensitive layer **22** with an X dipole illumination setting.

In FIG. **2** an exit pupil **26***a* associated with a light bundle is illustrated by a circle. The light bundle converges towards a field point that is located at a certain X position of the illumination field **14** at a first time during a scan cycle. In the exit pupil **26***a* two poles **27***a*, which are spaced apart along the X direction, represent directions from which projection light propagates towards this field point. The light energies concentrated in each pole **27***a* are assumed to be equal. Thus the projection light impinging from the +X direction has the same energy as the projection light impinging from the –X direction. Since the features **19** are assumed to be uniformly distributed over the pattern **18**, this X dipole illumination setting should be produced at each field point on the mask **16**.

Another exit pupil denoted by **26***b* is associated with a light bundle that converges towards a field point that is located at another X position of the illumination field **14** at a later time of the scan cycle. The light energies concentrated in each pole **27***b* are again equal. However, the light associated with the poles **27***b* are tilted compared to the light cones of light that are associated with the ideal pole **27***a*. This means that the field point receives the same amount of projection light, but the directions from which the projection light impinges on the field point are not ideal for imaging the features **19** on the light sensitive layer **22**.

A further exit pupil denoted by **26***c* is associated with a point in the illumination field **14** that is located at still another X position. Here it is assumed that the directions from which the projection light impinges on the field point are again ideal for imaging the features **19**. Therefore also the light cones associated with the poles **27***c* have the same cone angle and orientation as the cones associated with the ideal exit pupil **26***a*. However, the poles **27***c* are not balanced, i.e. the light energy concentrated in the poles **27***c* differs from one another. Thus the projection light impinging from the +X direction has less energy than the projection light impinging from the –X direction.

From the foregoing it becomes clear that the ideal angular irradiance distribution represented by the exit pupil **26***a* is not obtained at each X position in the illumination field **14**. The

angular irradiance distribution is therefore field-dependent, i.e. at different field points the angular irradiance distribution is different.

A field dependence may not only occur along the X direction, but also along the Y direction within the illumination field 14. Then one point on the mask 16 experiences different angular irradiance distributions while it passes through the illumination field 14 during a scan cycle. If a field dependence along the Y direction (i.e. the scan direction) occurs, it has to be taken into account that the total effect for a particular field point is obtained by integrating the different angular irradiance distributions.

There is a wide variety of further field-dependent deviations of a real angular irradiance distribution from the ideal one. For example, the poles in the exit pupil associated with some field points may be deformed, blurred or may not have a desired non-uniform irradiance distribution.

If field dependent deviations from the ideal angular irradiance distribution occur, this generally has a negative impact on the quality of the pattern image that is formed on the light sensitive layer 22. In particular, the dimensions of the structures that are produced with the help of the apparatus 10 may vary inadvertently, and this may compromise the function of the devices containing these structures. Therefore it is generally desired to eliminate any field dependence of the illumination setting in the illumination field 14.

Sometimes, however, it is desirable to deliberately introduce a field dependence of the angular irradiance distribution. This may be expedient, for example, if the projection objective 20 or the mask 16 have field depending properties that affect the image of the pattern 18 on the light sensitive layer 22. Variations of the imaging properties of the projection objective 20 may occur as a result of manufacturing tolerances, aging phenomena or non-uniform temperature distributions, for example. A field dependence of the mask 16 often occurs as a result of features that have different orientations or dimensions, for example. Often field dependent adverse effects can be successfully reduced by selectively introducing a field dependence of the angular irradiance distribution. Since some of these effects change very rapidly, it is sometimes desired to change the field dependence of the angular irradiance distribution during a single scan cycle.

III

General Construction of Illumination System

FIG. 3 is a meridional section through the illumination system 12 shown in FIG. 1. For the sake of clarity, the illustration of FIG. 3 is considerably simplified and not to scale. This particularly implies that different optical units are represented by one or very few optical elements only. In reality, these units may include significantly more lenses and other optical elements.

In the embodiment shown, the projection light emitted by the light source 11 enters a beam expansion unit 32 which outputs an expanded and almost collimated light beam 34. To this end the beam expansion unit 32 may include several lenses or may be realized as a mirror arrangement, for example.

The projection light beam 34 then enters a pupil forming unit 36 that is used to produce variable spatial irradiance distributions in a subsequent plane. To this end the pupil forming unit 36 includes a first mirror array 38 of very small mirrors 40 that can be tilted individually about two orthogonal axes with the help of actuators. FIG. 4 is a perspective view of the first mirror array 38 illustrating how two parallel

light beams 42, 44 are reflected into different directions depending on the tilting angles of the mirrors 40 on which the light beams 42, 44 impinge. In FIGS. 3 and 4 the first mirror array 38 includes only 6×6 mirrors 40; in reality the first mirror array 38 may include several hundreds or even several thousands mirrors 40.

The pupil forming unit 36 further includes a prism 46 having a first plane surface 48a and a second plane surface 48b that are both inclined with respect to an optical axis OA of the illumination system 12. At these inclined surfaces 48a, 48b impinging light is reflected by total internal reflection. The first surface 48a reflects the impinging light towards the mirrors 40 of the first mirror array 38, and the second surface 48b directs the light reflected from the mirrors 40 towards an exit surface 49 of the prism 46. The angular irradiance distribution of the light emerging from the exit surface 49 can thus be varied by individually tilting the mirrors 40 of the first mirror array 38. More details with regard to the pupil forming unit 36 can be gleaned from US 2009/0116093 A1.

The angular irradiance distribution produced by the pupil forming unit 36 is transformed into a spatial irradiance distribution with the help of a first condenser 50. The condenser 50, which may be dispensed with in other embodiments, directs the impinging light towards a digital spatial light modulator 52 that is configured to reflect impinging light in a spatially resolved manner. To this end the digital spatial light modulator 52 includes a second mirror array 54 of micromirrors 56 that are arranged in a mirror plane 57 and can be seen best in the enlarged cut-out C of FIG. 3 and the enlarged cut-out C' of FIG. 5. In contrast to the mirrors 40 of the first mirror array 38, however, each micromirror 56 of the second mirror array 54 has only two stable operating states, namely an "on" state, in which it directs impinging light via a first objective 58 towards an optical integrator 60, and an "off" state, in which it directs impinging towards a light absorbing surface 62.

The second mirror array 54 may be realized as a digital mirror device (DMD), as they are commonly used in beamers, for example. Such devices may include up to several million micromirrors that can be switched between the two operating states many thousands times per second.

Similar to the pupil forming unit 36, the spatial light modulator 52 further includes a prism 64 having an entrance surface 65 that is arranged perpendicular to the optical axis OA and a first plane surface 66a and a second plane surface 66b that are both inclined with respect to the optical axis OA of the illumination system 12. At these inclined surfaces 66a, 66b impinging light is reflected by total internal reflection. The first surface 66a reflects the impinging light towards the micromirrors 56 of the second mirror array 54, and the second surface 66b directs the light reflected from the micromirrors 56 towards a surface 68 of the prism 64.

If all micromirrors 56 of the second mirror array 54 are in their "on" state, the second mirror array 54 has substantially the effect of a plane beam folding mirror. However, if one or more micromirrors 56 are switched to their "off" state, the spatial irradiance distribution of the light emerging from the mirror plane 57 is modified. This can be used, in a manner that will be explained further below in more detail, to produce a field dependent modification of the angular light distribution on the mask 16.

As it already has been mentioned above, the light emerging from the prism 64 passes through the first objective 58 and impinges on the optical integrator 60. Since the light passing through the first objective 58 is almost collimated, the first objective 58 may have a very low numerical aperture (for example 0.01 or even below) and thus can be realized with a

few small spherical lenses. The first objective **58** images the mirror plane **57** of the spatial light modulator **52** onto the optical integrator **60**.

The optical integrator **60** includes, in the embodiment shown, a first array **70** and a second array **72** of optical raster elements **74**. FIG. **6** is a perspective view of the two arrays **70**, **72**. Each array **70**, **72** includes, on each side of a support plate, a parallel array of cylinder lenses extending along the X and the Y direction, respectively. The volumes where two cylinder lenses cross form optical raster elements **74**. Thus each optical raster element **74** may be regarded as a microlens having cylindrically curved surfaces. The use of cylinder lenses is advantageous particularly in those cases in which the refractive power of the optical raster elements **74** shall be different along the X and the Y direction. A different refractive power is used if the square irradiance distribution on the optical integrator **60** shall be transformed into a slit-shaped illumination field **14**, as this is usually the case. The surface of the optical raster elements **74** pointing towards the spatial light modulator **52** will be referred to in the following as light entrance facet **75**.

The optical raster elements **74** of the first and second array **70**, **72** respectively, are arranged one behind the other in such a way that one optical raster element **74** of the first array **70** is associated in a one to one correspondence with one optical raster element **74** of the second array **72**. The two optical raster elements **74**, which are associated with each other, are aligned along a common axis and define an optical channel. Within the optical integrator **60** a light beam which propagates in one optical channel does not cross or superimpose with light beams propagating in other optical channels. Thus the optical channels associated with the optical raster elements **74** are optically isolated from each other.

In this embodiment a pupil plane **76** of the illumination system **12** is located behind the second array **72**; however, it may equally be arranged in front of it. A second condenser **78** establishes a Fourier relationship between the pupil plane **76** and a mask plane **88** in which the mask **16** moves along the scan direction Y during a scan process scan cycle. Between the light entrance facets **75** of the optical integrator **60** and the mask **16** there is no field plane, i.e. no plane that is optically conjugate to the mask **16**. This is a remarkable feature of the illumination system **12**, because conventional illumination systems usually have an adjustable field stop that includes movable blades and is arranged in a field plane between the optical integrator **60** and the mask **16**. The movable blades ensure that the illumination field **14**, synchronized with the mask movement, opens and closes along the scan direction Y at the beginning and the end of each scan cycle, respectively. As it will become apparent from section IV.11 below, this function is performed in the illumination system **12** by a suitable control of the spatial light modulator **52**.

The mask plane **88** is thus optically conjugate to a raster field plane **84** which is located within or in close proximity to the light entrance facets **75** of the optical integrator **60**. This means that an irradiance distribution on each light entrance facet **75** in the raster field plane **84** is imaged onto the mask plane **88** by the associated optical raster element **74** of the second array **72** and the second condenser **78**. The images of the irradiance distributions (or light pattern) on the light entrance facet **75** within all optical channels superimpose in the mask plane **88**, which results in a very uniform illumination of the mask **16**.

Another way of describing the uniform illumination of the mask **16** is based on the irradiance distribution which is produced by each optical channel in the pupil plane **76**. This irradiance distribution is often referred to as secondary light

source. All secondary light sources commonly illuminate the mask plane **88** with projection light from different directions. If a secondary light source is "dark", no light impinges on the mask **16** from a (small) range of directions that is associated with this particular light source. Thus it is possible to set the desired angular light distribution on the mask **16** by simply switching on and off the secondary light sources formed in the pupil plane **76**. This is accomplished by changing the irradiance distribution on the optical integrator **60** with the help of the pupil forming unit **36**.

The pupil forming unit **36** and the spatial light modulator **52** are connected to a control unit **90** which is, in turn, connected to an overall system control **92** illustrated as a personal computer. The control unit **90** is configured to control the mirrors **40** of the pupil forming unit **36** and the micromirrors **56** of the spatial light modulator **52** in such a manner that the angular irradiance distribution in the mask plane **88** is uniform, or a desired field dependence angular irradiance distribution is obtained, and that the illumination field **14** opens and closes along the scan direction Y at the beginning and the end of the scan cycle.

In the following it will be described how this is accomplished.

IV

Function and Control of the Illumination System

1. Pupil Forming

FIG. **7** schematically illustrates how the pupil forming unit **36** produces an irradiance distribution on the micromirrors **56** of the spatial light modulator **52**. For the sake of simplicity the prisms **46**, **64** are not shown.

Each mirror **40** of the first mirror array **38** is configured to illuminate a spot **94** on the mirror plane **57** of the spatial light modulator **52** at a position that is variable by changing a deflection angle produced by the respective mirror **40**. Thus the spots **94** can be freely moved over the mirror plane **57** by tilting the mirrors **40** around their tilt axes. In this way it is possible to produce a wide variety of different irradiance distributions on the mirror plane **57**. The spots **94** may also partly or completely overlap, as this is shown at **95**. Then also graded irradiance distributions may be produced.

FIG. **8** is a perspective view, similar to FIG. **5**, on the second mirror array **54** contained in the spatial light modulator **52**. Here it is assumed that the pupil forming unit **36** has produced an irradiance distribution on the second mirror array **54** that consists of two square poles **27** each extending exactly over 6×6 micromirrors **56**. The poles **27** are arranged point-symmetrically along the X direction.

The objective **58** forms an image of this irradiance distribution on the light entrance facets **75** of the optical integrator **60**, as this is shown in FIG. **9**. Here it is assumed that all micromirrors **56** are in the "on"-state so that the irradiance distribution formed on the second mirror array **54** is identically reproduced (apart from a possible scaling due to a magnification of the objective **58**) on the light entrance facets **75** of the optical integrator **60**. For the sake of simplicity images of gaps that separate adjacent micromirrors **56** of the second mirror array **54** are disregarded. The regular grid shown on the light entrance facets **75** represent an image of the borderlines of the micromirrors **56**, but this image does not appear outside the poles **27** and is shown only in FIG. **9** for illustrative reasons.

2. Field Dependence

Since the light entrance facets **75** are located in the raster field plane **84**, the irradiance distribution on the light entrance

facets 75 is imaged, via the optical raster elements 74 of the second array 72 and the second condenser 78, on the mask plane 88.

This will now be explained with reference to FIG. 10 which is an enlarged and not to scale cut-out from FIG. 3. Here only two pairs of optical raster elements 74 of the optical integrator 60, the second condenser 78 and the mask plane 88 are shown schematically.

Two optical raster elements 74 that are associated with a single optical channel are referred to in the following as first microlens 101 and second microlens 102, respectively. The microlenses 101, 102 are sometimes referred to as field and pupil honeycomb lenses. Each pair of microlenses 101, 102 associated with a particular optical channel produces a secondary light source 106 in the pupil plane 76. In the upper half of FIG. 10 it is assumed that converging light bundles L1a, L2a and L3a illustrated with solid, dotted and broken lines, respectively, impinge on different points of the light entrance facet 75 of the first microlens 101. After having passed the two microlenses 101, 102 and the condenser 78, each light bundle L1a, L2a and L3a converges to a focal point F1, F2 and F3, respectively. From the upper half of FIG. 10 it becomes clear that points, where light rays impinge on the light entrance facet 75, and points where these light rays pass the mask plane 88 are optically conjugate.

The lower half of FIG. 10 illustrates the case when collimated light bundles L1b, L2b and L3b impinge on different regions of the light entrance facet 75 of the first microlens 101. This is the more realistic case because the light impinging on the optical integrator 60 is usually substantially collimated. The light bundles L1b, L2b and L3b are focused in a common focal point F located in the second microlens 102 and then pass, now collimated again, the mask plane 88. Again it can be seen that, as a result of the optical conjugation, the region where a light bundle L1b, L2b and L3b impinges on the light entrance facet 75 corresponds to a portion of the illumination field 14 in the mask plane 88. As a matter of course, these considerations apply separately for the X and the Y direction if the microlenses 101, 102 have refractive power both along the X and Y direction.

Therefore each point on a light entrance facet 75 directly corresponds to a conjugate point in the illumination field 14 in the mask plane 88. If it is possible to selectively influence the irradiance on a point on a light entrance facet 75, it is thus possible to influence the irradiance of a light ray that impinges on the conjugate point in the mask plane 88 from a direction that depends on the position of the light entrance facet 75 with respect to the optical axis OA of the illumination system. The larger the distance between a particular light entrance facet 75 from the optical axis OA is, the larger is the angle under which the light ray impinges on the point on the mask 16.

3. Modifying Irradiance on Light Entrance Facets

In the illumination system 12 the spatial light modulator 52 is used to modify the irradiance on points on the light entrance facets 75. In FIG. 9 it can be seen that each pole 27 extends over a plurality of small areas that are images of the micromirrors 56. If a micromirror is brought into an "off" state, the conjugate area on the light entrance facet 75 will not be illuminated, and consequently no projection light will impinge on a conjugate area on the mask from the (small) range of directions that is associated with this particular light entrance facet 75.

This will be explained in more detail with reference to FIGS. 11a and 11b which are top views on the micromirrors 56 of the spatial light modulator 52 and on the light entrance facets 75 of the optical integrator 60, respectively.

The thick dotted lines on the second mirror array 54 divide its mirror plane 57 into a plurality of object areas 110 each including 3×3 micromirrors 56. The objective 58 forms an image of each object area 110 on the optical integrator 60. This image will be referred to in the following as image area 110'. Each image area 110' completely coincides with a light entrance facet 75, i.e. the image areas 110' have the same shape, size and orientation as the light entrance facets 75 and are completely superimposed on the latter. Since each object area 110 includes 3×3 micromirrors 56, the image areas 110' also include 3×3 images 56' of micromirrors 56.

In FIG. 11a there are eight object areas 110 that are completely illuminated by the pupil forming unit 36 with projection light. These eight object areas 110 form the two poles 27. It can be seen that in some of the object areas 110 one, two or more micromirrors 56d represented as black squares have been controlled by the control unit 90 such that they are in an "off"-state in which impinging projection light is not directed towards the objective 58, but towards the absorber 62. By switching micromirrors between the "on" and the "off" state it is thus possible to variably prevent projection light from impinging on corresponding regions within the image areas 110' on the light entrance facets 75, as this is shown in FIG. 11b. These regions will be referred to in the following as dark spots 56d'.

As has been explained above with reference to FIG. 10, the irradiance distribution on the light entrance facets 75 is imaged on the mask plane 88. If a light entrance facet 75 contains one or more dark spots 56d', as this is illustrated in the upper portion of FIG. 12, the irradiance distribution produced in the mask plane 88 by the associated optical channel will have dark spots at certain X positions, too. If a point on a mask passes through the illumination field 14, the total scan integrated irradiance will thus depend on the X position of the point in the illumination field 14, as this is shown in the graph of FIG. 13. Points in the middle of the illumination field 14 will experience the highest scan integrated irradiance, because they do not pass through dark spots, and points at the longitudinal ends of the illumination field 14 will receive total irradiances that are reduced to different extents. Thus the field dependence of the angular light distribution on the mask 16 can be modified by selectively bringing one or more micromirrors 56 of the spatial light modulator 52 from an "on"-state into the "off"-state.

In a foregoing it has to be assumed that each object area 110, which is imaged on one of the light entrance facets 75, contains only 3×3 micromirrors 56. Thus the resolution along the cross-scan direction X that can be used to modify the field dependence of the angular light distribution is relatively coarse. If the number of micromirrors 56 within each object area 110 is increased, this resolution can be improved.

FIG. 14 illustrates a top view on one of the light entrance facets 75 for an embodiment in which 20×20 micromirrors 56 are contained in each object area 110. Then more complicated scan integrated irradiance distributions along the X direction can be achieved on the mask 16, as this is illustrated in the graph shown in FIG. 15.

4. Clipping

In the foregoing it has been assumed that the pupil forming unit 36 illuminates poles 27 on the second mirror array 54 that exactly extend over four adjacent object areas 110. Generally, however, it will be difficult to produce such an irradiance distribution with sharp edges.

The spatial light modulator 52 may also be used to clip a blurred irradiance distribution in the mirror plane 57 by bringing those micromirrors 56 into the "off"-state that lie outside the object areas 110 that shall be illuminated.

This is illustrated in FIGS. 16 and 17 in which an irradiance distribution 96 on the second mirror array 54 are shown. Here it is assumed that the movable light spots 94 produced by the mirrors 40 of the pupil forming unit 36 are superimposed to form four poles. If all micromirrors 56 of the spatial light modulator 52 are in the "on" state as shown in FIG. 16, the blurred irradiance distribution 96 would be imaged on the light entrance facets 75. If those micromirrors 56 surrounding the desired object areas 110 are brought into the "off"-state as shown in FIG. 17, they form a frame that delimits the poles and thus produces sharp edges of the intensity distribution on the light entrance facets.

5. Relative Rotation

In the embodiments described so far it has been assumed that the micromirrors 56 are aligned parallel to the borderlines of the object areas 110. The rectangular grid formed by the micromirrors 56 is then parallel to the rectangular grid which is formed by the light entrance facets 75. This results in irradiance distributions as shown in FIGS. 13 and 15 in which the irradiance along one "column" of micromirrors 56 is always uniform. Thus only stepped irradiance distributions can be produced on the light entrance facets 75.

Sometimes it is desirable to produce irradiance distributions that are not stepped, but contain inclined portions. This can be achieved if the two rectangular grids are not arranged parallel to each other, but with an angle α, as this is shown in FIG. 18. Here the images 56' of the micromirrors 56 form a grid 114 which forms an angle α with the lateral sides of the light entrance facet 75. Then the centers of adjacent micromirrors 56 are aligned along a straight line having an image 116 that forms the same angle α to a boundary line of the light entrance facet 75. If this angle α is distinct from m·45° with m=0, 1, 2, 3, . . . , the irradiance distribution will not have the shape of stepped profiles as shown in FIGS. 13 and 15.

FIG. 19 is a graph that illustrates the scan integrated irradiance distribution along the X direction for the rotated arrangement shown in FIG. 18. Some particular X positions are indicated in FIG. 18 with broken lines. If the angle α is distinct from m·45° with m=0, 1, 2, 3, . . . , the degeneration is reduced so that a desired attenuation can be obtained at more different X positions. In other words, it is thus possible to effectively increase the resolution along the X direction that is available to modify the field dependence of the angular irradiance distribution.

6a. Gaps—Lateral Displacement

As mentioned further above, it is usually inevitable that small gaps are formed between adjacent micromirrors 56 of the second mirror array 38. Images of these gaps are formed on the light entrance facets 75 and also on the mask 16. If these images extend parallel to the cross-scan direction X, this is of little concern because of the integrating effect that results from the scan operation. However, dark lines extending parallel to the scan direction Y could not be compensated by the integrating effect.

FIG. 20a shows in the upper portion a top view on one of the light entrance facets 75 in which the images of the gaps are denoted by 118'. The graph in the lower portion of FIG. 20a illustrates the irradiance distribution along the cross-scan direction X that is produced by this particular light entrance facet 75 in the mask plane 88. If all light entrance facets 75 would produce dark lines 120 at the same X positions, no projection light would reach points on the mask 16 at these positions.

FIGS. 20b and 20c show other light entrance facets 75 in which the gap images 118' are laterally displaced along the cross-scan direction X to different degrees. Consequently also the dark lines 120 in the irradiance distributions shown in the lower portion of these figures are laterally displaced. Since the irradiance distributions produced by each optical channel are superimposed in the mask plane 88, the dark lines 120 are averaged out, as this is shown in FIG. 21. The larger the number of light entrance facets 75 is and the smaller the dark lines 120 are, the more approximates the irradiance distribution I(x) in the mask plane 88 a uniform distribution.

6b. Gaps—Scattering Plate

Alternatively or additionally, a scattering plate 122 may be arranged in an optical path between the optical light modulator 52 and the mask plane 88 in order to avoid dark lines on the mask plane 88 caused by gap images 118'. Suitable positions of the scattering plate 122 are between the optical light modulator 52 and the objective 58, between the objective 58 and the optical integrator 60, or in the vicinity of the field stop plane 80.

FIG. 22 is a schematic meridional section showing several micromirrors 56 of the spatial light modulator 52, the objective 58 and the scattering plate 122 arranged in between. A gap 118 between two adjacent micromirrors 56 is assumed to have a width d, and the axial distance between the scattering plate 122 and the light exit surface 57 of the spatial light modulator 52 is denoted by b. If the characteristic scattering angle β of the scattering plate 122 is approximately d/b, the image of the gap 118 formed on the light entrance facet 75 is sufficiently blurred. If the scattering angle β is significantly larger than d/b, the desired spatial resolution for the field dependence of the irradiance and the angular irradiance distribution is reduced. If the scattering angle β is too small, the images of the gaps will still be prominent on the light entrance facets 75.

7. Rectangular Object Areas

In the embodiments described above it has been assumed that the number of micromirrors 56 along the scan direction Y and the cross-scan direction X is identical. Then a rectangular grid of square micromirrors 56 perfectly fits into a square light entrance facet 75 of the optical integrator 60.

The number N_X of micromirrors 56 along the cross-scan direction X determines the resolution that is available for adjusting the field dependence of the irradiance and the angular irradiance distribution. This number should be as high as possible.

The number N_Y of micromirrors 56 along the scan direction Y may be significantly smaller because of the integrating effect caused by the scan operation. Illustratively speaking, a plurality of optical channels adjacent along the scan direction Y may contribute to the reduction of the irradiance on a point on the mask 16 during a scan cycle. This does not apply to optical channels that are adjacent along the cross-scan direction X.

These requirements suggest that the object area 110 may well be rectangular, with the length along the cross-scan direction X being larger (for example two times and preferably at least five times larger) than the length of the object area along the scan direction Y. Assuming micromirrors 56 having equal dimensions along the directions X and Y, this implies that the number N_X of micromirrors 56 along the cross-scan direction X is larger than the number N_Y along the scan direction Y.

If a rectangular object area 110 shall be imaged on a square light entrance facet 75, the objective 58 has to be anamorphotic. More specifically, the absolute value of the magnification M has to be smaller along the cross-scan direction X than along the scan direction Y, i.e. $|M_X|<|M_Y|$. This is illustrated in FIG. 23 in which two cylinder lenses 124, 126 of the objective 58 are arranged between a single rectangular object area 110 and the light entrance facet 75 of an optical raster

element **74**. If the length of the object area **110** along the cross-scan direction X is L_X and the length along the scan direction Y is L_Y, $|M_X/M_Y|$ should be equal to L_Y/L_X.

A similar result is achieved if not the objective **58**, but the subsequent condenser **78** is anamorphotic so that its focal length f is different for the X and Y directions. If the objective **58** is rotational symmetric so that $M_X=M_Y$, the irradiance distributions on the light entrance facets **75** will be rectangular with the same aspect ratio L_X/L_Y as the object area **110**. This rectangular irradiance distribution is then expanded by the anamorphotic condenser **78** so that a square irradiance distribution is obtained in the field stop plane **80** and the subsequent mask plane **88**. This approach may involve a redesign of the optical integrator **60** because the condenser's different focal lengths along the directions X, Y have to be compensated by the refractive power of the optical raster elements **74**.

8. Arrangement of Mirror Plane

It is usually preferred if the chief rays of the projection light impinge perpendicularly on the optical integrator **60**. Then also the mirror plane **57**, which is imaged by the objective **58** on the light entrance facets **75**, is arranged perpendicularly to the optical axis OA, as this is shown in FIG. **24**. In such a parallel arrangement of the micromirrors **56** and the light entrance facets **75** the micromirrors **56** have to produce a deflection angle which is distinct from zero if they are in the "on"-state. This is different to conventional digital mirror devices (DMD) in which all mirror surfaces are arranged in a single plane if they are in the "on"-state.

Additionally or alternatively, the second mirror array **54** and the light entrance facets **75** may be arranged in off-axis regions of the object field and the image field of the objective **58**, respectively. As it is shown in FIG. **25**, it is then possible to use an objective **58** such that it is not telecentric on the object side, but telecentric on the image side. This means that chief rays forming an angle with the optical axis OA on the object side are nevertheless parallel to the optical axis OA on the image side.

9. Grouping Object Areas

If the number of micromirrors **56** in each object area **110** and also the number of optical channels (and thus of the light entrance facets **75**) shall be large, the total number of micromirrors **56** in the second mirror array **54** may become huge. Since it might be difficult to provide a single second mirror array **54** that includes such a huge number of micromirrors **56**, it is envisaged to split up the second mirror device into several sub-units. More specifically, the second mirror array **54** may be combined from several groups of object areas, wherein the groups are separated from each other by dark areas (i.e. an area from which no projection light emerges) that are not imaged on the light entrance facets. Each group may be realized as a single device, for example a digital mirror device (DMD).

FIG. **26** is a schematic meridional section through the second mirror array **54** and the objective **58** according to this embodiment. It is assumed that the second mirror array **54** includes two groups **54-1**, **54-2** each realized as digital mirror device (DMD). Each group **54-1**, **54-2** includes three object areas **110** that extend over a plurality of micromirrors **56**. The two groups **54-1**, **54-2** are separated by a dark area **130** which is absorptive and on which no projection light should be directed by the pupil forming unit **36**.

The objective **58** is configured to combine the images **110'** of the object areas **110** so that they abut at least substantially seamlessly on the optical integrator **60**. There each image area **110'** completely coincides with one of the light entrance facets **75**. To this end the objective **58** produces magnified

images of the object areas **110** in an intermediate image plane **132** with the help of a first array of lenses **134**. The objective **58** further includes an array of second lenses **136** that is arranged in the intermediate image plane **132**. Common imaging optics **138** then image the intermediate image plane **134**, in which the magnified images of the groups already abut, on the light entrance facets **75** of the optical integrator **60**. In this way the dark areas **130** between the groups **54-1**, **54-2** is not imaged by the objective **58** on the optical integrator **60**.

10. Diffractive Optical Element and LCD

FIG. **27** is a meridional section similar to FIG. **3** of an alternative embodiment of an illumination system **12**. In this illumination system the pupil forming unit **52** is replaced by a diffractive optical element **142**, zoom optics **144** and a pair of axicon elements **146**, **148**.

The spatial light modulator **52** in this embodiment is formed by an LCD panel including a two dimensional array of minute LCD cells whose optical activity can be controlled individually by the control unit **90**. If the projection light produced by the light source **11** is not sufficiently polarized, an additional polarizer may be inserted in the light path in front of the spatial light modulator **52**.

As a matter of course, the embodiments shown in FIGS. **3** and **27** can also be combined in different ways so that, for example, a diffractive optical element **142** is used together with the second mirror array **54** as spatial light modulator **52**.

11. Field Stop Blade Function

In the illumination system **12** shown in FIG. **3** there is, as it has already been mentioned further above, no field plane between the light entrance facets **75** and the mask plane **88** (see also FIG. **10**). In conventional illumination systems the opening and closing of the illumination field **14** at the beginning and the end of each scan cycle, respectively, is accomplished by movable blades of a field stop arranged in a field plane between the optical integrator **60** and the mask **16**. In the illumination system **12** of the present disclosure this function is taken over by a suitable control of the second mirror array **54**.

This will be explained in the following with reference to FIGS. **28a** to **28h**. These figures show, at different stages during a scan cycle, at the left hand side a schematic top view on one of the object areas **110** on the light exit surface **57** of the second mirror array **54**. Here it is assumed that 9×9 digital micromirrors **56** are arranged within the object area **110**.

Next to the object area **110** a corresponding image area **110'** is schematically shown. Here it is assumed that the objective **58** images the object area **110** at a reduced scale on one of the light entrance facets **75** of the optical integrator **60**. Since each light entrance facet **75** is optically conjugate to the mask plane **88**, a light pattern in the image area **110'** is reproduced in the mask plane **88**. In the embodiment shown this image is compressed along the scan direction Y because the optical raster elements **74**, **75** have different refractive power along the X and Y direction. For that reason the fully opened illumination field **14** is slit-shaped although the image fields **110'** on the light entrance facets **75** are square.

In order to avoid gaps between adjacent micromirrors **56** causing dark stripes in the illumination field **14**, different object areas **110** may be laterally displaced with respect to each other, as this has been explained above in section IV.6a, and/or a scattering plate may be provided, as this has been explained above in section IV.6b. For the sake of simplicity the effects of such gaps are neglected in the following.

At the right end side of each FIGS. **28a** to **28h** the mask **16** is shown. The mask **16** is provided with an opaque rim **150** that surrounds a central area **152** containing the small features

19 to be imaged on the light sensitive surface 22. The opaque rim 150 includes a front side 156 and a rear side 158 both extending along the cross-scan direction X, and two lateral sides 160 extending along the scan direction Y. The width of the front side 156 and the rear side 158 of the opaque rim 150 is denoted by w.

FIG. 28a illustrates the situation before a scan cycle begins. All micromirrors 56 of the second mirror array 54 are in the "off" state, and thus the corresponding image area 110' on the light entrance facet 75 is not illuminated.

Then a first row 162-1 of micromirrors 56 is brought into the "on" state, as this is shown in FIG. 28b. The light pattern formed on the light entrance facet 75 is a narrow stripe being an image of the first row 162-1. At the very moment when the first row 162-1 of micromirrors 56 is brought into the "on" state, the image of the narrow stripe, which now forms the illumination field 14, is positioned completely on the front side 156 of the opaque rim 150. Thus there are not yet any features 19 illuminated with projection light; only the front side 156 of the opaque rim 150 is illuminated, and the projection light is completely absorbed by the opaque rim 150.

As the mask 16 moves further along the scan direction Y, the thin illumination field 14 evenly enters the central area 152 that is surrounded by the opaque rim 150. Now the imaging of the features 19 begins. If seen along the scan direction Y, the length of the light pattern formed on the light entrance facet 75, and thus also its image on the mask 16, increases continuously, while the length in the cross-scan direction X remains constant.

Then the next row 162-2 of micromirrors 56 is brought into the "on" state, as this is shown in FIG. 28c. As can be seen in the enlarged cutout, one half 164 of the illumination field 14 illuminates only the front side 156 of the opaque rim 150 where the projection light is absorbed, and the other half 166 of the illumination field 14 illuminates the features 19 in the central area 152 of the mask 16.

Then the next row of micromirrors 56 is brought into the "on" state, and so on. This process is continued until all micromirrors 56 are in the "on" state, as this is shown in FIG. 28d. Now the illumination field 14 has its full length along the scan direction Y. The fully opened illumination field 14 is positioned at this moment so that it abuts the front side 156 of the opaque rim 150.

As the mask 16 moves further along the scan direction Y, the illumination field 14 now having its full length along the scan direction Y continuously scans over the features 19 in the central area 152 of the mask 16, as this is shown in FIG. 28e. In this manner the mask 16 is scanned until the illumination field 14 abuts the rear side 158 of the opaque rim 150, as this is shown in FIG. 28f. Now the illumination field 14 begins to enter the rear side 158 of the opaque rim 150 where the projection light is absorbed. When the image of the row 162-1 of micromirrors 56 is arranged completely on the opaque rim 150, the micromirrors 56 of the first row 162-1 are brought into the "off" state. The length of the image of the light pattern on the light entrance facet 75, i.e. the illumination field 14, along the scan direction Y now decreases.

As soon as the image of the second row 162-2 is arranged completely on the rear side 158 of the opaque rim 150, the micromirrors 56 of the second row 162-2 are brought into the "off" state, and so on.

FIG. 28g illustrates a state in which the first five rows 162-1 to 162-5 have been brought into the "off" state. The length of the illumination field 14 along the scan direction Y has meanwhile decreased by more than one half.

When all micromirrors 56 are again in the "off" state, the illumination field 14 is completely closed, and no light reaches the mask 16, as this is shown in FIG. 28h.

V

Important Method Steps

Important method steps of the present disclosure will now be summarized with reference to the flow diagram shown in FIG. 29.

In a first step S1 a spatial light modulator having a light exit surface is illuminated.

In a second step S2 a light pattern in an object area on the light exit surface is produced.

In a third step S3 an intermediate image of the light pattern on a light entrance facet of an optical integrator and a final image on a mask are formed.

In a fourth step S4, while the mask moves along a scan direction, the light pattern on the object area is changed so that a length of the final image along the scan direction gradually increases at the beginning of a scan cycle and gradually decreases at the end of the scan cycle.

What is claimed is:

1. An illumination system configured to illuminate an object moving along a scan direction, the illumination system comprising:
   an optical integrator configured so that, during use of the illumination system, the optical integrator produces a plurality of secondary light sources in a pupil plane of the illumination system, the optical integrator comprising a plurality of light entrance facets, each light entrance facet associated with a secondary light source, and the optical integrator configured so that, during use of the illumination system, images of the light entrance facets at least substantially superimpose in the object plane;
   a spatial light modulator having a light exit surface, the spatial light modulator configured so that, during use of the illumination system, the spatial light modulator transmits or reflects impinging projection light in a spatially resolved manner;
   a pupil forming unit configured so that, during use of the illumination system, the pupil forming unit directs projection light onto the spatial light modulator;
   an objective configured so that, during use of the illumination system, the objective images the light exit surface of the spatial light modulator onto the light entrance facets of the optical integrator so that an image of an object area on the light exit surface completely coincides with one of the light entrance facets; and
   a control unit configured so that, during use of the illumination system, the control unit controls the spatial light modulator so that along the scan direction a length of an image, which is formed on the object from a light pattern in the object area, gradually increases at a beginning of a scan cycle and gradually decreases at the end of the scan cycle,
   wherein the illumination system is a microlithographic illumination system.

2. The illumination system of claim 1, wherein the pupil forming unit comprises a first beam deflection array of first reflective or transparent beam deflection elements, and each beam deflection element is configured so that, during use of the illumination system, the beam deflection element illumi-

nates a spot on the spatial light modulator at a position that is variable by changing a deflection angle produced by the beam deflection element.

3. The illumination system of claim 1, wherein:

the spatial light modulator comprises a beam deflection array of reflective or transparent beam deflection elements;

each beam deflection element configurable in an on state and in an off state;

for each beam deflection element, the beam deflection element is configured so that during use of the illumination system:

when in its on state, the beam deflection element directs impinging projection light toward the optical integrator; and

when its off state, the beam deflection element directs impinging projection light elsewhere.

4. The illumination system of claim 3, wherein the beam deflection array comprises a digital mirror device.

5. The illumination system of claim 3, wherein at least 10 beam deflection elements are arranged in the object area.

6. The illumination system of claim 3, wherein:

centers of adjacent beam deflection elements in the object area are aligned along a straight line;

an image of the straight line defines an angle with respect to a boundary line of the one of the light entrance facets; and

the angle is distinct from $m \cdot 45°$ with $m=0, 1, 2, 3, \ldots$.

7. The illumination system of claim 6, wherein:

boundaries of the beam deflection elements are arranged in a first rectangular grid;

boundaries of the light entrance facets are arranged in a second rectangular grid; and

an image of the first rectangular grid formed on the light entrance facets forms the angle to the second rectangular grid.

8. The illumination system of claim 3, wherein a length of the object area along a first direction is larger than a length of the object area along a second direction which is orthogonal to the first direction, and the objective is an anamorphotic objective having a magnification M with |M| being smaller along the first direction than along the second direction.

9. The illumination system of claim 8, wherein the second direction corresponds to the scan direction.

10. The illumination system of claim 3, further comprising a scattering plate dispose so that, during use of the illumination system, the scattering plate is in a light path between the optical light modulator and the object plane.

11. The illumination system of claim 3, wherein the control unit is configured so that, during use of the illumination system, the control unit controls the spatial light modulator so that rows of adjacent beam deflection elements are simultaneously brought from the off state to the on state and vice versa during the scan cycle.

12. The illumination system of claim 2, wherein the light spots produced by the beam deflection elements on the object area are larger than the object area.

13. The illumination system of claim 1, wherein:

the light exit surface of the optical light modulator comprises groups of object areas which are separated by areas that are not imaged on the light entrance facets during use of the illumination system;

the objective is configured so that, during use of the illumination system, the objective combines images of the object areas so that the images of the object areas abut on the optical integrator.

14. The illumination system of claim 13, wherein the objective comprises:

a first array of first optical elements, each first optical element configured so that, during use of the illumination system, the first optical element forms a magnified image of one of the groups in an intermediate image plane; and

imaging optics configured so that, during use of the illumination optics, the imaging optics image the intermediate image plane onto the light entrance facets.

15. The illumination system of claim 1, wherein the control unit is configured so that, during use of the illumination system, the control unit controls the spatial light modulator so that the image, which is formed on the object from the light pattern in the object area, has a length along a cross-scan direction, which is perpendicular to the scan direction, that remains constant during the scan cycle.

16. The illumination system of claim 1, wherein, between the light entrance facets and the object, there is no plane that is optically conjugate to the object.

17. An apparatus, comprising:

an illumination system according to claim 1; and

a projection objective,

wherein the apparatus is a microlithographic projection exposure apparatus.

18. A method of using an apparatus comprising an illumination system and a projection objective, the method comprising:

using the illumination system to illuminate at least some structures of a mask; and

using the projection objective to image at least a portion of the illuminated structures onto a light-sensitive material,

wherein the illumination system is an illumination system according to claim 1.

19. An apparatus, comprising:

an illumination system according to claim 3; and

a projection objective,

wherein the apparatus is a microlithographic projection exposure apparatus.

20. The apparatus of claim 19, wherein the object comprises a mask with a light absorbing stripe extending perpendicular to the scan direction and having a width along the scan direction which is greater than or equal to a length along the scan direction of an image of one of the beam deflection elements formed on the object plane during use of the apparatus.

21. An illumination system configured to illuminate an object, the illumination system comprising:

a spatial light modulator configured so that, during use of the illumination system, the spatial light modulator transmits or to reflects impinging light in a spatially resolved manner;

a pupil forming unit configured so that, during use of the illumination system, the pupil forming unit directs light on the spatial light modulator;

an optical integrator configured so that, during use of the illumination system, the optical integrator produces a plurality of secondary light sources located in a pupil plane, the optical integrator comprising a plurality of light entrance facets, each light entrance facet being associated with one of the secondary light sources; and

an objective configured so that, during use of the illumination system, the objective images a light exit surface of the spatial light modulator onto the light entrance facets of the optical integrator,

wherein:

between the light entrance facets and the object plane, there is no plane that is optically conjugate to the object plane; and

the illumination system is a microlithographic illumination system.

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CERTIFICATE OF CORRECTION

PATENT NO.	: 9,310,690 B2	Page 1 of 1
APPLICATION NO.	: 14/543110	
DATED	: April 12, 2016	
INVENTOR(S)	: Markus Deguenther et al.	

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Specification

Col. 3, line 25, delete "i.e" and insert -- i.e. --.

Col. 3, line 43, delete "close" and insert -- dose --.

Col. 15, line 39, delete "process scan".

Signed and Sealed this
Nineteenth Day of July, 2016

Michelle K. Lee
Director of the United States Patent and Trademark Office